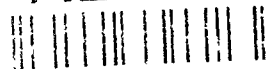


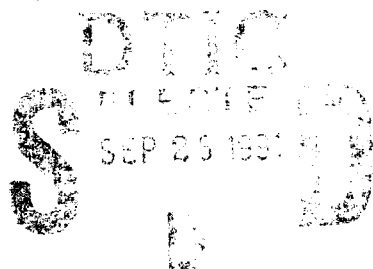
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Technical Report  
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# Application of Adaptive Nulling to Electromagnetic Hyperthermia for Improved Thermal Dose Distribution in Cancer Therapy



A.J. Fenn

3 July 1991

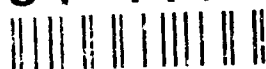
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## ERRATA

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Errors in the production process require the following corrections:

The figure on page 59 is Figure A-6, and belongs with the caption on page 61.

The figure on page 60 is Figure A-7, and belongs with the caption on page 62.

The figure on page 61 is Figure A-4, and belongs with the caption on page 59.

The figure on page 62 is Figure A-5, and belongs with the caption on page 60.

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**APPLICATION OF ADAPTIVE NULLING TO  
ELECTROMAGNETIC HYPERTHERMIA FOR  
IMPROVED THERMAL DOSE DISTRIBUTION  
IN CANCER THERAPY**

*A.J. FENN*  
*Group 61*

TECHNICAL REPORT 917

3 JULY 1991

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## ABSTRACT

Adaptive nulling is applied to the problem of generating a therapeutic thermal dose distribution in electromagnetic hyperthermia treatment of cancer. A system design concept for implementing adaptive hyperthermia is introduced. With the proposed design concept, it may be possible to maximize the applied electric field at a tumor position in the target body and simultaneously minimize or reduce the electric field at target positions where undesired high temperature regions (hot spots) occur. In a clinical situation, either a gradient search algorithm or sample matrix inversion algorithm would be used to rapidly form the adaptive null (or nulls) prior to any significant tissue heating. Auxiliary short-dipole field probes are used in effecting the desired electric field nulls. An adaptive null formed at the surface of the target has a finite width and extends into the target. This finite null width can allow for noninvasively positioned auxiliary probes in an adaptive hyperthermia system. The allowed spacing or resolution between a deep null and focus is fundamentally equal to the hyperthermia antenna half-power beamwidth in the tissue. A closer spacing between the desired null position and focus is achieved by reducing the null depth via the signal-to-noise ratio at the auxiliary probe.

Analysis of an annular phased-array antenna embedded in an infinite homogeneous medium shows the potential merit of combining adaptive nulling with conventional near-field focusing used in hyperthermia. The analysis is based on a well-known moment-method theory for conducting thin-wire antennas in a homogeneous conducting medium. The theory and software used to compute the moment-method received voltage at a short-dipole probe due to a transmitting dipole array are documented. Computer simulation results are presented for a fully adaptive eight-element annular array operating at 120 MHz and embedded in homogeneous muscle tissue. Multiple simultaneous nulls are used in adaptively generating a desired radiation pattern in the muscle tissue. The power received at a movable short-dipole E-field sensor is then used as the power source in a second computer simulation that performs a transient thermal analysis of an elliptical target body surrounded by a constant-temperature water bolus. The computer simulations show that adaptive nulling can prevent undesired high-temperature regions from occurring while simultaneously heating a deep-seated tumor site.



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## TABLE OF CONTENTS

Abstract	iii
List of Illustrations	vii
Acknowledgments	viii
1. INTRODUCTION	1
2. THEORY	7
2.1 Noninvasive Adaptive Hyperthermia System Concept	7
2.2 Adaptive Transmit Array Formulation	12
2.3 Moment-Method Formulation	16
3. SIMULATION RESULTS	27
3.1 Electric Field for Array in Homogeneous Tissue	28
3.2 Temperature Distribution in Elliptical Phantom	40
4. CONCLUSION	53
APPENDIX A - SYSTEM DEGRADATION DUE TO INSUFFICIENT NUMBER OF AUXILIARY PROBES	55
APPENDIX B - SOFTWARE DOCUMENTATION	63
REFERENCES	99

## LIST OF ILLUSTRATIONS

Figure No.		Page
1	A clinical hyperthermia phased-array antenna system.	2
2	General concept for focused near-field adaptive nulling.	4
3	Two applications of focused near-field adaptive nulling: (a) Radar system testing and (b) Hyperthermia treatment of cancer.	5
4	Noninvasive adaptive hyperthermia system concept.	8
5	(a) Transverse cross section at the prostate level. An eight-element hyperthermia ring array of dipole elements is used to irradiate a target body with sufficient power to elevate the temperature of the target body to a therapeutic level. (b) Elliptical phantom target used to model the prostate (target)-level cross section. Shown are four noninvasive auxiliary E-field probes that are used in forming null zones with widths controlled by the individual null depths. The null zones extend into the body to reduce the internal electric field at specified locations.	9
6	Simulated two-dimensional thermal pattern at time $t = 20$ minutes in elliptical phantom muscle-tissue target surrounded with $10^{\circ}\text{C}$ constant-temperature water bolus. The incident RF power distribution is at 120 MHz and the initial temperature of the phantom is $25^{\circ}\text{C}$ . Temperature contour levels are given in $2^{\circ}\text{C}$ steps. (a) Before nulling: hot spots on the left and right sides of the target are present. (b) After nulling: hot spots are eliminated.	10
7	Adaptive transmit phased-array antenna near-field focusing concept.	11
8	Implementation of the SMI algorithm for an adaptive hyperthermia system. Four performance measures are used in evaluating the adaptive response of the system: electric-field distribution, covariance matrix eigenvalues, adaptive transmit weights, and interference cancellation.	13
9	Transmit array and receive antenna probe. Open-circuit mutual impedance between array elements is denoted $Z_{m,n}$ . The open-circuit voltage at the probe is computed from the array terminal currents and from $Z_n^j$ , the open-circuit mutual impedance between the $n$ th array element and the $j$ th probe antenna.	17
10	Equivalent circuit model for receive antenna probe.	17

## LIST OF ILLUSTRATIONS (Continued)

Figure No.		Page
11	Equivalent circuit model used in thermal analysis. The inhomogeneous body of interest is modeled with a grid of nodes interconnected by resistors. Each node has an associated power source and capacitor.	24
12	The moment-method simulation's use with the transient thermal analysis. RF power distribution over the target region is converted into a time-dependent temperature distribution.	26
13	Geometry for eight-element ring array and four E-field auxiliary sensors.	30
14	Simulated two-dimensional quiescent radiation pattern at 120 MHz for uniformly illuminated eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue: $\epsilon_r = 73.5, \sigma = 0.5$ ). A fictitious elliptical target region is indicated by the dashed curve. Radiation contour levels are in 10-dB steps.	31
15	Simulated two-dimensional quiescent radiation pattern at 120 MHz for uniformly illuminated eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue: $\epsilon_r = 73.5, \sigma = 0.5$ ). A fictitious elliptical target region is indicated by the dashed curve. Radiation contour levels are given in 1-dB steps.	32
16	Simulated one-dimensional quiescent radiation pattern cut ( $z = 0$ ) at 120 MHz for uniformly illuminated eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue: $\epsilon_r = 73.5, \sigma = 0.5$ ).	33
17	Simulated one-dimensional quiescent radiation pattern cut ( $x = 0$ ) at 120 MHz for uniformly illuminated eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue: $\epsilon_r = 73.5, \sigma = 0.5$ ).	34
18	Simulated two-dimensional adaptive radiation pattern at 120 MHz for eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue: $\epsilon_r = 73.5, \sigma = 0.5$ ). Radiation contour levels are given in 10-dB steps. Four auxiliary sensors are used in forming the adaptive pattern. The quiescent focus is at (0.0).	36
19	Simulated one-dimensional quiescent and adaptive radiation patterns in the $z = 0$ cut at 120 MHz for eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue: $\epsilon_r = 73.5, \sigma = 0.5$ ). Four auxiliary sensors are used in forming the adaptive pattern.	37



## LIST OF ILLUSTRATIONS (Continued)

Figure No.		Page
20	Simulated one-dimensional quiescent and adaptive radiation patterns in the $x = 0$ cut at 120 MHz for eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue: $\epsilon_r = 73.5, \sigma = 0.5$ ). Four auxiliary sensors are used in forming the adaptive pattern.	38
21	Transmit array weights before and after adaptive nulling. A dynamic range of about 5 dB is evident for the adaptive weights. Four auxiliary sensors are used in the adaptive process. (a) Amplitude; (b) Phase.	39
22	Channel covariance matrix eigenvalues (degrees of freedom) used in the adaptive process with four auxiliary sensors.	40
23	Simulated two-dimensional thermal pattern at time $t = 20$ minutes before nulling in elliptical phantom muscle-tissue target surrounded with 10°C constant-temperature water bolus. The incident RF power distribution, from Figure 14, is at 120 MHz. Temperature contour levels are given in 2°C steps. Hot spots on the left and right sides of the target are observed.	42
24	Simulated one-dimensional ( $z = 0$ ) thermal pattern at time $t = 20$ minutes before nulling in elliptical phantom muscle-tissue target surrounded with 10°C constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. Hot spots on the left and right sides of the target are observed.	43
25	Simulated one-dimensional ( $x = 0$ ) thermal pattern at time $t = 20$ minutes before nulling in elliptical phantom muscle-tissue target surrounded with 10°C constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. No hot spots are present.	44
26	Simulated two-dimensional thermal pattern at time $t = 20$ minutes (with adaptive nulling at four auxiliary sensors in effect) in elliptical phantom muscle-tissue target surrounded with 10°C constant-temperature water bolus. The adapted incident RF power distribution, from Figure 18, is at 120 MHz. Temperature contour levels are given in 2°C steps. Hot spots on the left and right sides of the target are eliminated.	45

## LIST OF ILLUSTRATIONS (Continued)

Figure No.		Page
27	Simulated one-dimensional ( $z = 0$ ) thermal patterns at time $t = 20$ minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with $10^{\circ}\text{C}$ constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. Hot spots on the left and right sides of the target are clearly eliminated by the adaptive nulling process. Four auxiliary sensors are used in the adaptive process.	46
28	Simulated one-dimensional ( $x = 0$ ) thermal patterns at time $t = 20$ minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with $10^{\circ}\text{C}$ constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. No undesired hot spots are present. Four auxiliary sensors are used in the adaptive process.	47
29	E-field probe-sample-spacing convergence check for simulated two-dimensional thermal pattern at time $t = 20$ minutes (before adaptive nulling) in elliptical phantom muscle-tissue target surrounded with $10^{\circ}\text{C}$ constant-temperature water bolus. The quiescent incident RF power distribution is at 120 MHz. Temperature contour levels are given in $2^{\circ}\text{C}$ steps. The grid spacing is one-half the spacing of that in Figure 23. Hot spots on the left and right sides of the target are present, as previously observed for the coarser probe-sample spacing.	48
30	E-field probe-sample-spacing convergence check for simulated two-dimensional thermal pattern at time $t = 20$ minutes (with adaptive nulling in effect) in elliptical phantom muscle-tissue target surrounded with $10^{\circ}\text{C}$ constant-temperature water bolus. The adapted incident RF power distribution is at 120 MHz. Temperature contour levels are given in $2^{\circ}\text{C}$ steps. The grid spacing is one-half the spacing of that in Figure 26. Hot spots on the left and right sides of the target are eliminated, as previously observed for the coarser probe-sample spacing.	49

## LIST OF ILLUSTRATIONS (Continued)

Figure No.		Page
31	E-field probe-sample-spacing convergence check for simulated one-dimensional ( $z = 0$ ) thermal patterns at time $t = 20$ minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with $10^{\circ}\text{C}$ constant-temperature water bolus. The quiescent incident RF power distribution is at 120 MHz with 0.9525-cm sample spacing. Hot spots on the left and right sides of the target are eliminated by the adaptive nulling process, as previously observed in Figure 27. Four auxiliary sensors are used in the adaptive process.	50
32	E-field probe-sample-spacing convergence check for simulated one-dimensional ( $x = 0$ ) thermal patterns at time $t = 20$ minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with $10^{\circ}\text{C}$ constant-temperature water bolus. The quiescent incident RF power distribution is at 120 MHz with 0.9525-cm sample spacing. No undesired hot spots are present. Four auxiliary sensors are used in the adaptive process.	51
A-1	Geometry for eight-element ring array and two E-field auxiliary sensors.	55
A-2	Simulated two-dimensional adaptive radiation pattern at 120 MHz for eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue: $\epsilon_r = 73.5$ , $\sigma = 0.5$ ). Radiation contour levels are given in 10-dB steps. Two auxiliary sensors are used in forming the adaptive pattern. The quiescent focus is at (0,0).	57
A-3	Simulated two-dimensional thermal pattern at time $t = 20$ minutes (with adaptive nulling at only two auxiliary sensors in effect) in elliptical phantom muscle-tissue target surrounded with $10^{\circ}\text{C}$ constant-temperature water bolus. The adapted incident RF power distribution, from Figure 18, is at 120 MHz. Temperature contour levels are given in $2^{\circ}\text{C}$ steps. Initial hot spots (before nulling) on the left and right sides of the target (see Figure 23) are redistributed to the top and bottom (anterior and posterior positions).	58
A-4	Simulated one-dimensional ( $z = 0$ ) thermal patterns at time $t = 20$ minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with $10^{\circ}\text{C}$ constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. Hot spots on the left and right sides of the target are eliminated by the adaptive nulling process. Two auxiliary sensors are used in the adaptive process.	59

## LIST OF ILLUSTRATIONS

### (Continued)

Figure No.		Page
A-5	Simulated one-dimensional ( $x = 0$ ) thermal patterns at time $t = 20$ minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with $10^{\circ}\text{C}$ constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. Two undesired hot spots are present in the adaptive pattern. Two auxiliary sensors are used in the adaptive process.	60
A-6	Transmit array weights before and after adaptive nulling. A dynamic range of about 7 dB is evident for the adaptive weights. Two auxiliary sensors are used in the adaptive process. (a) Amplitude; (b) Phase.	61
A-7	Channel covariance matrix eigenvalues (degrees of freedom) used in the adaptive process with two auxiliary sensors.	62

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## 1. INTRODUCTION

The successful treatment of deep-seated malignant tumors within a patient is often a difficult task. The objective of the treatment is to reduce in size or completely remove the tumor mass by one or more modalities available at the treatment facility. Common modalities are surgery, chemotherapy, and x-ray therapy [1]. A modality used alone or in conjunction with one of the above modalities is "tissue heating," or hyperthermia [1,2,3,4]. Hyperthermia can be considered as a form of high fever within the body; a controlled thermal dose distribution is required for hyperthermia to have a therapeutic value. Typical localized-hyperthermia temperatures required for therapeutic treatment of cancer are in the 43–45°C range. Normal tissue should be kept at temperatures below 43°C during the treatment. The most difficult aspect of implementing hyperthermia, with either radio-frequency (RF) waves or acoustic (ultrasound) waves, is producing sufficient heating at depth. Multiple-applicator RF hyperthermia arrays are commonly used to provide a focused near-field main beam at the tumor position. A focal region should be concentrated at the tumor with minimal energy delivered to surrounding normal tissue. As the hyperthermia antenna beamwidth is proportional to the wavelength, a small focal region suggests that the RF wavelength be as small as possible. However, due to propagation losses in tissue, the RF depth of penetration decreases with increasing transmit frequency. One of the major problems in heating a deep-seated tumor with a hyperthermia antenna is the formation of undesired "hot spots" in surrounding tissue. This additional undesired heating often produces pain, burns, and blistering in the patient, which requires terminating the treatment immediately. The patient does not receive anesthetics during the hyperthermia treatment in order to provide direct verbal feedback of any pain. Thus, techniques for reducing hot spots are necessary in hyperthermia treatment.

Several journals have published special issues on acoustic and electromagnetic hyperthermia treatment of cancer [5,6]. Electromagnetic transmitting arrays in the frequency band 60–2000 MHz are used to localize heating of malignant tumors within a target body. Many studies have been conducted to produce improved therapeutic field distributions with hyperthermia phased arrays [7–20]. Phase control can be used to synthesize therapeutic RF radiation patterns without adaptive control of the transmit array weights [7–12]. Array transmit weights can be adaptively controlled to maximize the tumor temperature (or RF power delivered to the tumor) while minimizing the surrounding tissue temperature (or RF power delivered to the surrounding tissue) [13–20]. All other studies require invasive techniques to optimize the radiation pattern [13–20]. This report addresses the potential benefit of using adaptive nulling with noninvasive auxiliary sensors to reduce the field intensity at selected positions in the target body while maintaining a desired focus at a tumor.

It is useful to describe certain features of a clinical hyperthermia system used to treat deep-seated tumors. A hyperthermia annular phased-array antenna system (Model BSD-2000, SIGMA-60 applicator [21], BSD Medical Corporation, Salt Lake City, Utah) is shown in Figure 1. By fully surrounding the patient with an annular phased array, it is possible to obtain constructive interference (or signal enhancement) deep within the target volume. This hyperthermia system uses a 60-cm array diameter with eight uniformly spaced dipole elements operating over the frequency

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WATER  
BOLUS



DIPOLE PAIR

BSD MEDICAL CORP. MODEL BSD-2000	
OPERATING FREQ.	60-120 MHz
NO. CHANNELS	4
POWER	500 W/CHANNEL
ANTENNA	8-DIPOLE RING

Figure 1. A clinical hyperthermia phased-array antenna system.

band 60–120 MHz [22]. The eight dipoles are fed as four active pairs of elements. There are four high-power amplifiers which drive the dipole pairs with up to 500 W average power per channel. Each of the four active channels has an electronically controlled variable-phase shifter for focusing the array. Temperature and electric-field probe sensors (both invasive and noninvasive) are used to monitor the treatment. A cool-water (5–40°C) bolus between the patient and the phased array is used to prevent excess heating of the skin surface. The bolus is filled with circulating distilled water, which has a very low propagation loss. Computer simulation models for this hyperthermia antenna system with inhomogeneous targets have been developed [7,9]. To the author's knowledge, the hyperthermia system in Figure 1 has not been used to form adaptive nulls, although the system may have sufficient temperature and electric-field sensing capability to implement adaptive nulling with an appropriate transmit-weight control algorithm. A candidate adaptive nulling algorithm would be a gradient search based on minimizing the signal received by electric-field sensors at the desired null positions while maximizing the signal at the focal point. The reason for considering this algorithm is that the BSD-2000 system is currently capable of measuring the applied electric-field amplitude but not the phase. Note: the E-field detectors used in the BSD-2000 system are semiconductor diode detectors. A potentially better approach to performing adaptive hyperthermia is to use a channel-covariance-matrix-based algorithm to control the weights. If the electric-field phase and amplitude are measured (by modification of the E-field probe hardware to form in-phase and quadrature signals) the sample matrix inversion (SMI) algorithm [23] could be used to form the nulls. The concept of adaptive nulling as it applies to hyperthermia will now be described.

Recently, the author has been investigating a technique called focused near-field adaptive nulling [24–30], for which the general concept is shown in Figure 2. A calibration probe antenna is used to focus the main beam at approximately one diameter  $D$  of the phased array. Additional (auxiliary) probe antennas are located in the sidelobe region of the phased-array quiescent radiation pattern. Adaptive nulls are formed in the direction of these auxiliary probes. Computer simulations show that a radar system can be tested by using the focused near-field nulling technique [29]. Experimental measurements of focused near-field adaptive nulling are available [30]. During the radar system testing study, similarities between the radar application and electromagnetic hyperthermia were noticed by the author. These similarities are that 1) phased-array near-field focusing is used to form the main beam and 2) uncontrolled or high sidelobes are potentially deleterious to system performance. For the radar system, interference signals entering through uncontrolled sidelobes can reduce the signal-to-noise ratio (SNR); adaptive nulling [31] is commonly used to counteract this possible degradation. In the hyperthermia system, high-transmit antenna sidelobes can give rise to hot spots in the target tissue. These high-temperature regions could possibly be alleviated with adaptive nulling of the electric-field sidelobes in the target. Much of the software developed for the radar system testing analysis may be readily modified to handle adaptive hyperthermia analysis.

There is continued interest at Lincoln Laboratory in applying techniques used in Department of Defense (DoD)-sponsored research to other disciplines, such as medical applications. This study applies radar system testing technology (currently in the form of software simulation) to the medical application of hyperthermia. Figure 3 depicts the similarities between radar system near-field



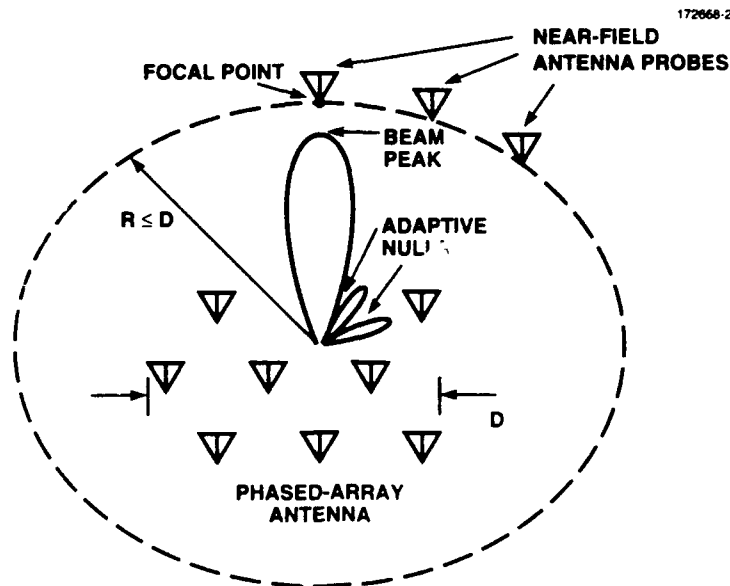


Figure 2. General concept for focused near-field adaptive nulling.

testing and electromagnetic hyperthermia treatment of cancer. In Figure 3(a), a radar phased-array antenna system is positioned in an anechoic test chamber with radiating sources that simulate typical radar signals. Notice that the test antenna is focused in the near field at one aperture diameter. Computer simulations have shown that the near-field signals (jammer, radar clutter, and target) received and processed by an adaptive radar system are equivalent to fielded radar conditions [29]. In Figure 3(b), a hyperthermia (transmit) phased array is used to therapeutically illuminate a target body by focusing its electromagnetic energy on a malignant tumor deep within the body. Nulls are formed adaptively to reduce the electromagnetic energy delivered to potential hot spots. The nulls are shown invasive to the target; however, noninvasive null positions on the surface of the target are also possible as shown in this report.

An example of a deep-seated tumor is cancer of the prostate [1]. The tumor volume often has a decreased blood flow which aids in heating the tumor, compared to normal tissue for which heat is carried away by normal blood flow. Note: a blood-flow thermal analysis [32,33] is beyond the scope of this report; we would like to show initially that with a computer simulation of RF-illuminated phantom muscle tissue [34] adaptive nulling can improve the thermal dose distribution. The thermal analysis used in this report is similar to the method presented in Zhang, et al. [35], where blood flow effects are ignored. In practice, undesired high-temperature regions away from the focus can occur inside the target volume. For example, scar tissue, which has a decreased blood flow rate, will tend to heat up more rapidly than normal tissue. In the proposed adaptive hyperthermia concept, electric-field nulls are used to reduce the power delivered to potential hot

spots. Computer simulations show that noninvasive field probes can be used to eliminate hot spots interior to the phantom target tissue.

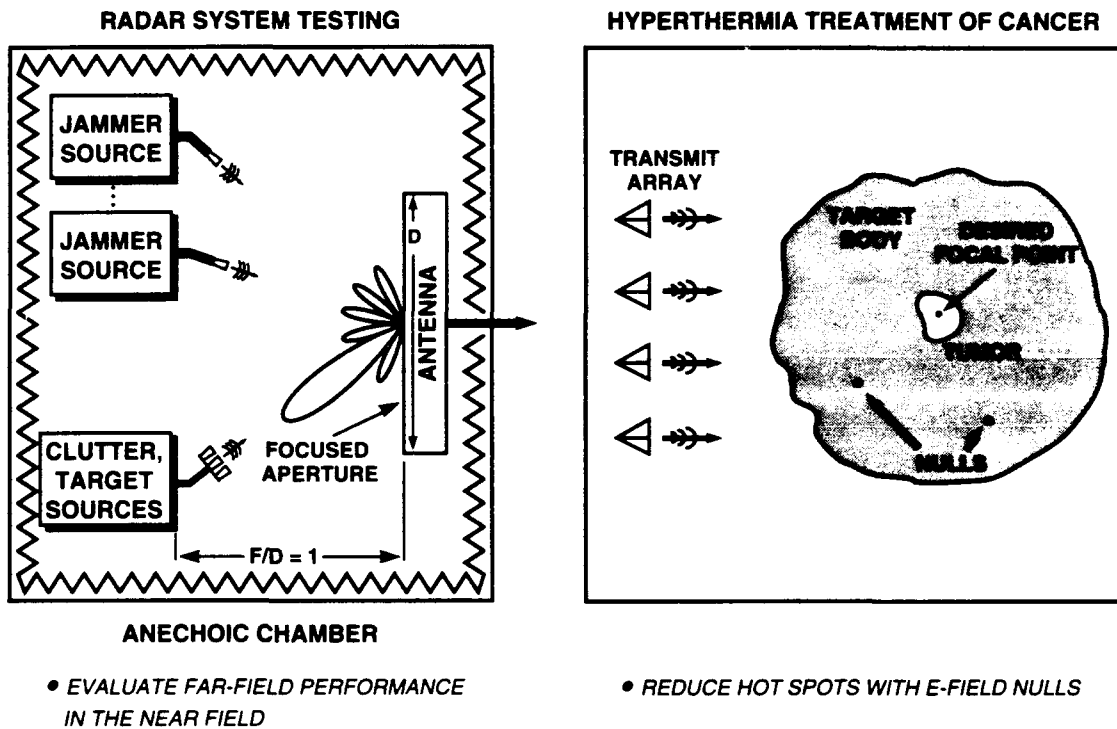


Figure 3. Two applications of focused near-field adaptive nulling: (a) Radar system testing and (b) Hyperthermia treatment of cancer.

An antenna analysis code (called WIRES) capable of analyzing a wide variety of antenna or radar cross section problems has been developed by J.H. Richmond [36–38]. The software can analyze complex geometries involving multiple-connected and/or isolated wires and is well-suited to analyzing low-frequency phased arrays radiating into an infinite homogeneous conducting medium. WIRES is a moment-method code that uses the electric field integral equation (EFIE) to enforce the boundary condition of the tangential electric field being zero at the surface of the antenna of interest. The moment-method basis and testing functions used in this code are piecewise sinusoidal. For a complete description of the theory and capabilities of the WIRES code, the reader is referred to the user's manual [37]. The WIRES software has been modified by the author to include near-field focusing and adaptive nulling capabilities. This modified code has been used to analyze the

near-field and far-field adaptive nulling performance of thin-wire phased arrays in free space [27,29]. A new version of the thin-wire code that can analyze adaptive hyperthermia arrays in an infinite homogeneous conducting medium has recently been written and is documented in this report.

This report is organized in the following manner. Section 2 discusses the concept for a noninvasive adaptive hyperthermia system and describes in detail the theory used in performing the focused near-field adaptive nulling simulation. Pertinent theory for wave propagation in a conducting medium is reviewed. A brief description of the transient thermal analysis approach used to compute the temperature distribution in a target is given. Section 3 presents simulation results for a fully adaptive eight-element hyperthermia ring array operating at 120 MHz. The calculated received RF-power distributions, before and after adaptive nulling, at a short-dipole field probe with both the field probe and the hyperthermia array embedded in homogeneous muscle tissue, are presented. The RF power distribution is then fed into transient thermal analysis software which computes the two-dimensional temperature distribution in an elliptical muscle-tissue target surrounded with a constant-temperature water bolus. The temperature distribution obtained by using multiple independent adaptive nulls clearly indicates the elimination of undesired hot spots. Conclusions are made in Section 4. Performance degradation due to insufficient number of auxiliary null positions is described in Appendix A. Appendix B contains data files and source code for the focused near-field adaptive nulling computer simulations.

## 2. THEORY

### 2.1 NONINVASIVE ADAPTIVE HYPERTHERMIA SYSTEM CONCEPT

The concept of a noninvasive adaptive-nulling hyperthermia system [39,40] is shown in Figure 4. Theoretically, to generate the desired field distribution in a clinical adaptive hyperthermia system, receiving sensors are positioned as close as possible to the focus (tumor site) and to where high temperatures are to be avoided (such as near the spinal cord and scar tissue). As simulations in this report will show, for an annular array configuration the receiving sensors can be located noninvasively on the surface (skin) of the target. Initially, the hyperthermia array is focused to produce the required field intensity at the tumor. An invasive probe is required to achieve the optimum focus at depth. To avoid undesired hot spots, it is necessary to minimize the power received at the desired null positions and to constrain the array weights to deliver a required amount of transmitted or focal region power. The adaptive array weights (with gain  $g$  and phase  $\phi$ ) are controlled by either the SMI algorithm or a gradient search algorithm to rapidly (within seconds) form the nulls before a significant amount of target heating takes place. With this adaptive technique, it should be possible to avoid unintentional hot spots and maintain a therapeutic thermal dose distribution at the tumor.

Figure 5(a) shows a specific example of an eight-element hyperthermia ring phased array with a target cross section at the prostate level [9]. Figure 5(b) shows an elliptical phantom target which is used to model the prostate-level cross section. A noninvasive adaptive nulling system is achieved by placing auxiliary sensors  $1, 2, \dots, N_{aux}$  on the target skin as shown. The null zones centered at each auxiliary probe naturally extend into the elliptical target region to eliminate undesired hot spots. (An example of a two-dimensional near-field null zone is shown in Figure 10(b) of Fenn [28]). The width of each null zone is directly related to the depth of each null. The depth of each null (sometimes referred to as the amount of cancellation) is directly related to the SNR at the sensor position. A low SNR produces a small amount of nulling, and a high SNR produces a large amount of nulling. The resolution or minimum spacing between the focus and null position is normally equal to the half-power beamwidth of the antenna. The resolution is enhanced somewhat by using weak nulls whenever the separation between the null and focus is closer than the half-power beamwidth.

Figure 6 summarizes the thermal simulation for a hyperthermia ring array transmitting into a homogeneous elliptical target region. The tumor site is assumed to be at the center of the ellipse. The thermal distribution in Figure 6(a) contains two undesired hot spots to the left and right of the focus. In Figure 6(b), adaptive nulling is applied and the hot spots are eliminated. The details of the computer simulations are contained in Section 3.

In the near-field nulling technique described here, it is assumed that the hyperthermia phased-array antenna is focused (as it normally is) in the near field and that a main beam and possibly sidelobes are formed in the target. In this report, it is assumed that phase focusing is used to produce the desired quiescent main beam. Figure 7 shows a primary (calibration) probe antenna located at a desired focal point of an array. The array can maximize the signal received by the

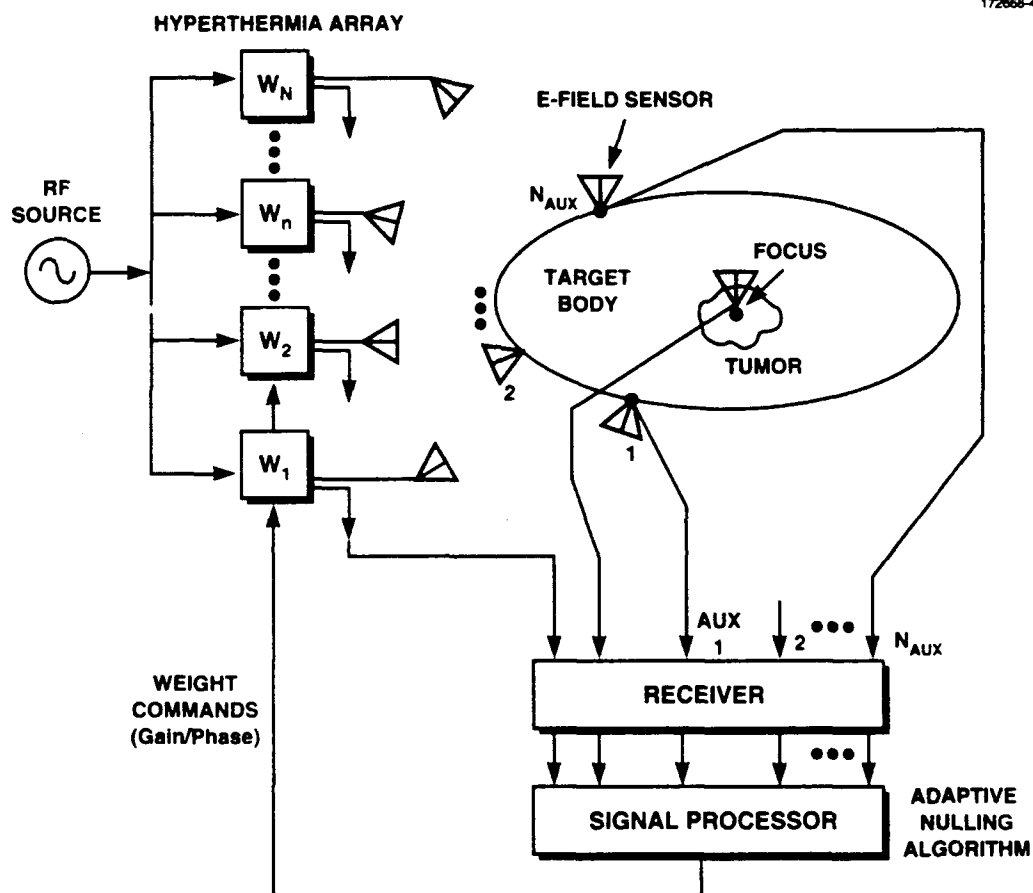


Figure 4. Noninvasive adaptive hyperthermia system concept.

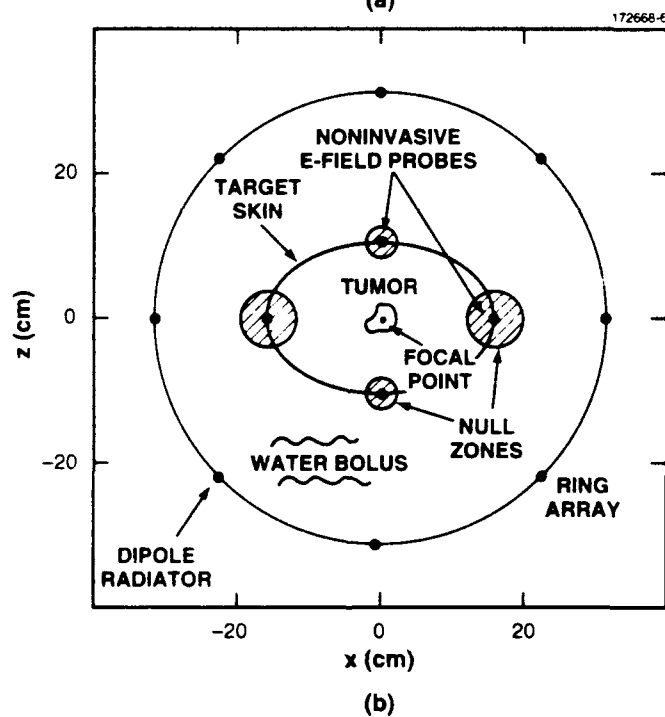
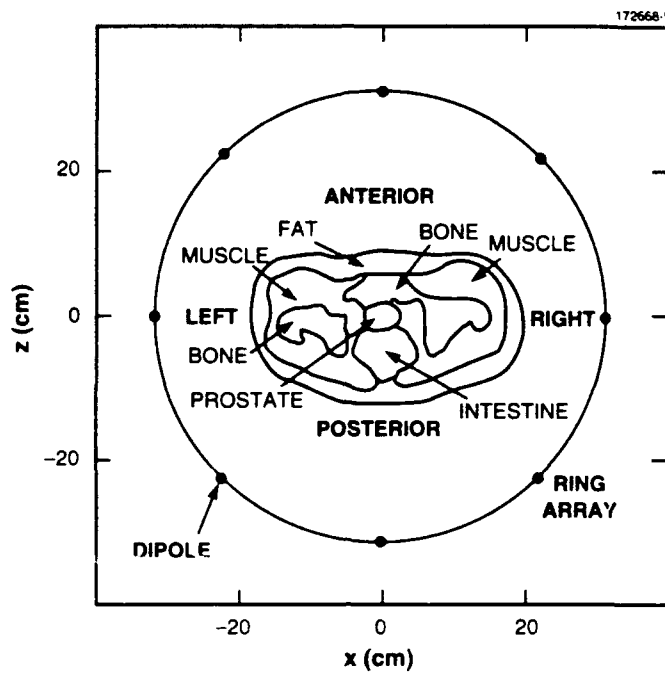
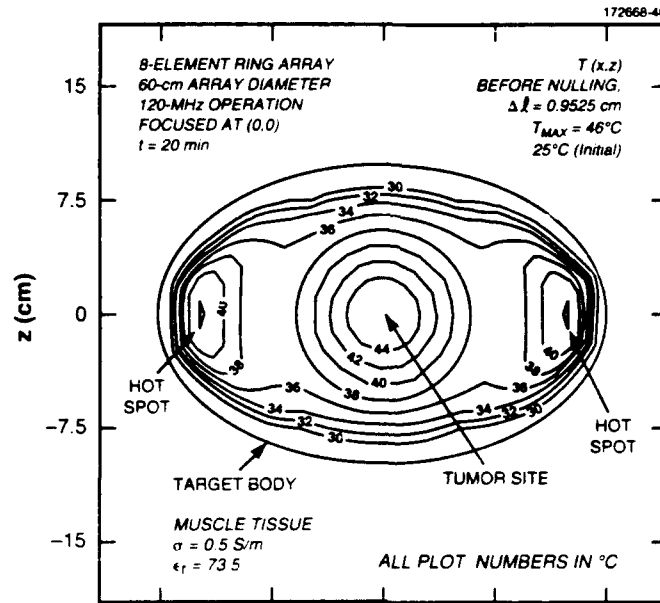
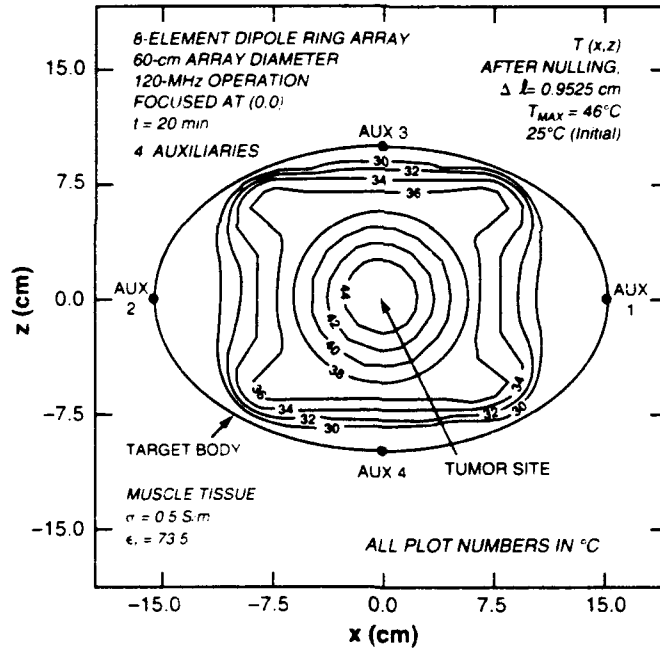


Figure 5. (a) Transverse cross section at the prostate level. An eight-element hyperthermia ring array of dipole elements is used to irradiate a target body with sufficient power to elevate the temperature of the target body to a therapeutic level. (b) Elliptical phantom target used to model the prostate (target)-level cross section. Shown are four noninvasive auxiliary E-field probes that are used in forming null zones with widths controlled by the individual null depths. The null zones extend into the body to reduce the internal electric field at specified locations.



(a)



(b)

Figure 6. Simulated two-dimensional thermal pattern at time  $t = 20$  minutes in elliptical phantom muscle-tissue target surrounded with  $10^\circ\text{C}$  constant-temperature water bolus. The incident RF power distribution is at 120 MHz and the initial temperature of the phantom is  $25^\circ\text{C}$ . Temperature contour levels are given in  $2^\circ\text{C}$  steps. (a) Before nulling; hot spots on the left and right sides of the target are present. (b) After nulling; hot spots are eliminated.

calibration probe by adjusting its phase shifters so that the observed element-to-element phase variation is removed. One way to do this in a numerical simulation is to choose a reference path length as the distance from the focal point to the phase center of the array. This distance is denoted  $r_F$  and the distance from the focal point to the  $n$ th array element is denoted  $r_n^F$ . The voltage received at a probe (located at the focal point) due to the  $n$ th array element is computed here using the method of moments as described in Section 2.3. To maximize the received voltage at the focal-point probe output, it is necessary to apply the phase conjugate of the observed signals, due to the array elements, at the transmit array. The resulting near-field radiation pattern will have a main beam and sidelobes. The main beam will be pointed at the array focal point, and sidelobes will exist at angles away from the main beam. Auxiliary probe antennas can then be placed at the desired null positions in the quiescent sidelobe region. These sidelobes are where tissue hot spots are likely to occur; they are nulled by the adaptive nulling algorithms described below.

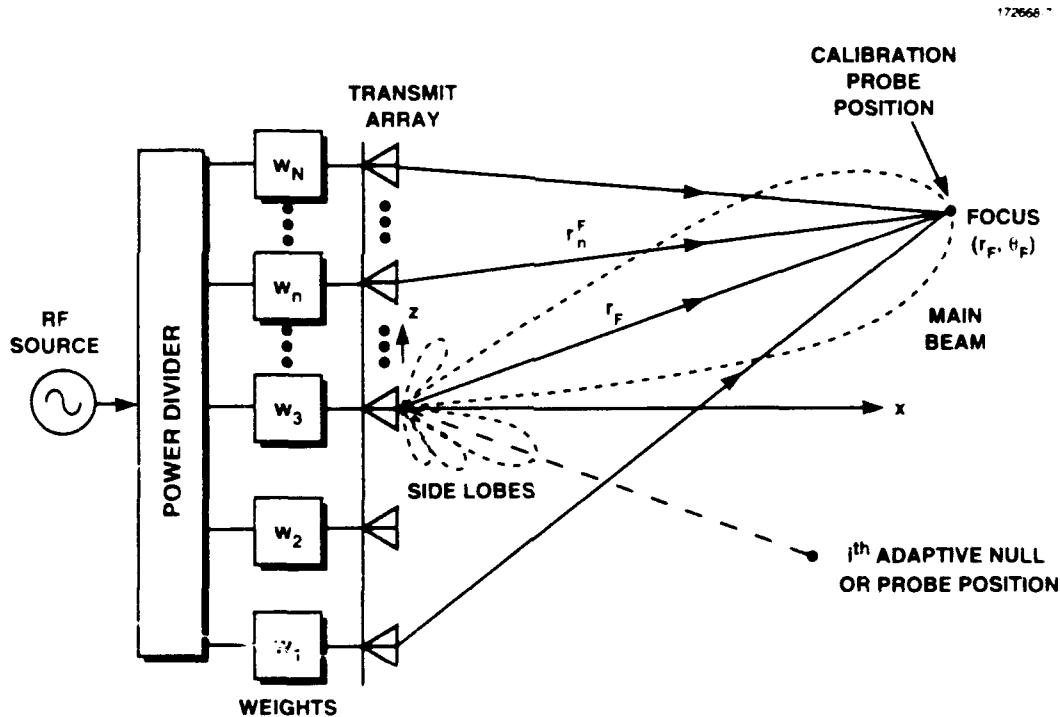


Figure 7. Adaptive transmit phased-array antenna near-field focusing concept.



## 2.2 ADAPTIVE TRANSMIT ARRAY FORMULATION

Consider the hyperthermia array and probe geometry shown in Figure 7. Typically, the hyperthermia array contains  $N$  identical antenna elements. The input signal to each of the  $N$  array elements is obtained from the weighted signal distributed by the power divider. The number of adaptive channels is denoted  $M$ , and for a fully adaptive array  $M = N$ . Note: the report will concentrate on fully adaptive arrays (arrays in which all transmit array elements have adaptive weight control); however, the computer simulation program is developed for both fully adaptive and sidelobe canceller arrays. In this report, ideal transmit weights (a complex voltage gain vector) are assumed in the computer simulation, with  $\mathbf{w} = (w_1, w_2, \dots, w_N)^T$  denoting the adaptive channel weight vector as shown in Figure 4.<sup>1</sup> (Superscript  $T$  means transpose). To generate adaptive nulls, the transmit weights (phase and gain) are controlled by either the SMI algorithm or a gradient search algorithm. The SMI algorithm has the flexibility to operate in either open- or closed-loop feedback modes [41]; the gradient search algorithm operates only in a feedback mode.

### 2.2.1 Sample Matrix Inversion Algorithm

With the SMI algorithm [23], the fundamental quantities required to fully characterize the incident field for adaptive nulling purposes are the adaptive channel cross correlations. To implement this algorithm it is necessary to know the complex received voltage at the auxiliary probes. For example, the moment-method formulation (described in Section 2.3) allows computation of the complex-received voltage at the auxiliary probes.

The block diagram in Figure 8 shows how the SMI algorithm is used in the hyperthermia analysis. The diagram indicates four performance measures used to quantify the computer simulations: electric-field distribution, covariance matrix eigenvalues, adaptive transmit weights, and interference cancellation. The calculation of these performance measures is described in detail below.

Referencing Figure 7, let a spheric,<sup>1</sup> wavefront be incident at the  $i$ th probe antenna, due to each array element (radiating one at a time with a unity-amplitude reference signal), which results in a set of probe-received complex voltages denoted  $v_1^i, v_2^i, \dots, v_N^i$ . The cross correlation  $R_{mn}^i$  of the received voltages due to the  $m$ th and  $n$ th adaptive transmit channels at the  $i$ th probe is given by

$$R_{mn}^i = \mathbf{E}(v_m v_n^*) \quad (1)$$

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<sup>1</sup>The effects of transmit-weight quantization and transmit-weight random errors are addressed in the software.

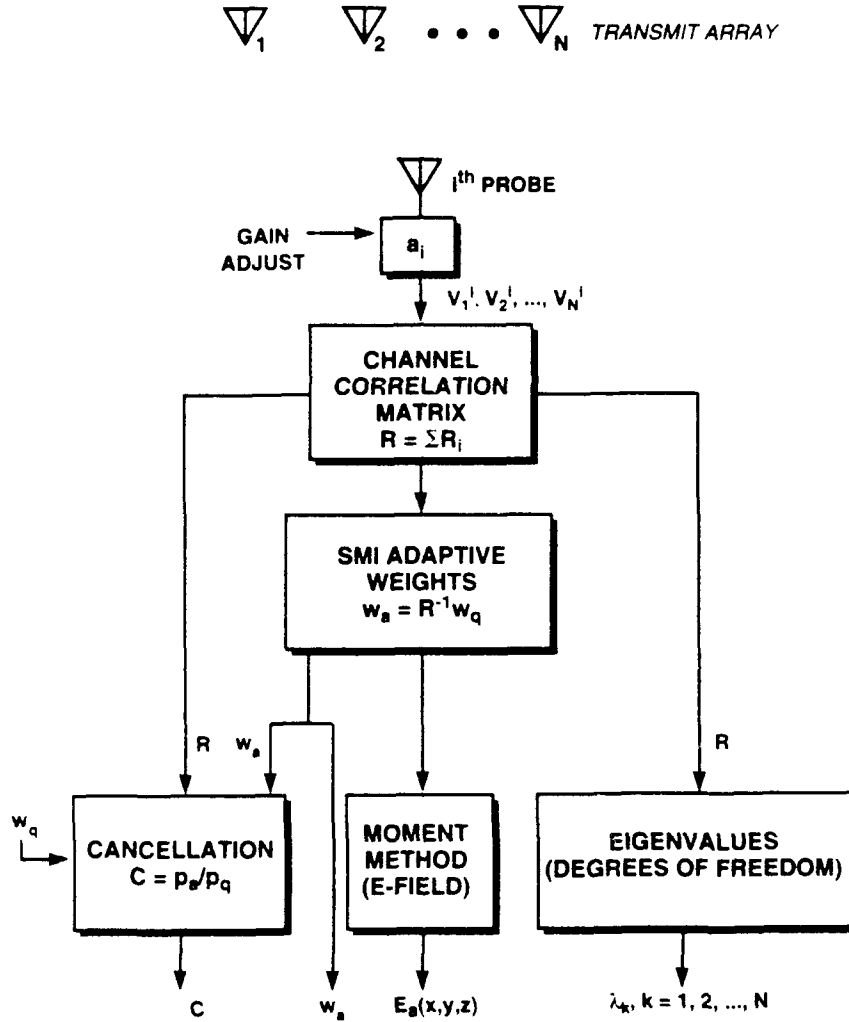


Figure 8. Implementation of the SMI algorithm for an adaptive hyperthermia system. Four performance measures are used in evaluating the adaptive response of the system: electric-field distribution, covariance matrix eigenvalues, adaptive transmit weights, and interference cancellation.

where  $*$  means complex conjugate and  $E(\cdot)$  means mathematical expectation. Because  $v_m$  and  $v_n$  represent voltages of the same waveform but at different times,  $R_{mn}^i$  is also referred to as an autocorrelation function. Note: for convenience, in Equation (1) the superscript  $i$  in  $v_m$  and in  $v_n$  has been omitted.

In the frequency domain, assuming the transmit waveform has a band-limited white noise power spectral density (as commonly assumed in jamming of a radar system), Equation (1) can be expressed as the frequency average

$$R_{mn}^i = \frac{1}{B} \int_{f_1}^{f_2} v_m(f) v_n^*(f) df \quad , \quad (2)$$

where  $B = f_2 - f_1$  is the nulling bandwidth and  $f$  is the frequency. It should be noted that  $v_m(f)$  takes into account the transmit wavefront shape, which is spherical for the hyperthermia application. For the special case of a continuous wave (CW) transmit waveform, as normally used in hyperthermia, the cross correlation reduces to

$$R_{mn}^i = v_m(f_o) v_n^*(f_o) \quad , \quad (3)$$

where  $f_o$  is the transmit frequency of the hyperthermia array.

Let the channel or interference covariance matrix be denoted  $\mathbf{R}$ . (Note: in hyperthermia, interference is used to refer to the signals received at the auxiliary probes. The undesired hot spots can be thought of as interfering with the therapy.) If there are  $J_{aux}$  independent desired null positions or auxiliary probes, the  $J_{aux}$ -probe covariance matrix is the sum of the covariance matrices observed at the individual probes; that is,

$$\mathbf{R} = \sum_{i=1}^{J_{aux}} \mathbf{R}_i + \mathbf{I} \quad . \quad (4)$$

where  $\mathbf{R}_i$  is the sample covariance matrix observed at the  $i$ th probe and  $\mathbf{I}$  is the identity matrix used to represent the thermal noise level of the receiver. (It should be noted that both  $N_{aux}$  and  $J_{aux}$  can be used interchangeably to describe the number of auxiliary nulling sensors or received-interference signal positions. The symbol  $J_{aux}$  is perhaps more descriptive and can equivalently be thought of as the number of positions where jamming signals are nulled).

Prior to generating an adaptive null, the adaptive channel weight vector,  $\mathbf{w}$ , is chosen to synthesize a desired quiescent radiation pattern. When nulling is desired, the optimum set of transmit weights to form an adaptive null (or nulls), denoted  $\mathbf{w}_a$ , is computed [23] by

$$\mathbf{w}_a = \mathbf{R}^{-1} \mathbf{w}_q \quad , \quad (5)$$

where  $^{-1}$  means inverse and  $\mathbf{w}_q$  is the quiescent weight vector. During array calibration, the normalized quiescent transmit weight vector, with element 1 radiating, is chosen to be  $\mathbf{w}_q = (1, 0, 0, \dots, 0)^T$ ; that is, the transmit channel weight of element 1 is unity and the remaining transmit channel weights are zero. Similar weight settings are used to calibrate the remaining transmit elements. For a fully adaptive annular array focused at the origin in homogeneous tissue, the normalized quiescent weight vector is simply  $\mathbf{w}_q = (1, 1, 1, \dots, 1)^T$ . Commonly, the weight vector is constrained to deliver a required amount of power to the hyperthermia array or to the tumor. For simplicity in the software used to analyze the hyperthermia array, the weights are constrained such that

$$\sum_{n=1}^M |u_n|^2 = 1 \quad , \quad (6)$$

where  $u_n$  is the transmit weight for the  $n$ th element. Note: in the computer simulations, the electric field due to the normalized weight vector is scaled appropriately to deliver the required amount of power to the tissue so that a desired focal-region temperature level is achieved after  $t$  minutes.

The summation of power received at the probes is given by

$$p = \mathbf{w}^\dagger \mathbf{R} \mathbf{w} \quad , \quad (7)$$

where  $^\dagger$  means complex conjugate transpose. The interference-plus-noise-to-noise ratio, denoted  $INR$ , is computed as the ratio of the auxiliary probe array output power [defined in Equation (7)] with the transmit signal present to the probe array output power with only receiver noise present; that is,

$$INR = \frac{\mathbf{w}^\dagger \mathbf{R} \mathbf{w}}{\mathbf{w}^\dagger \mathbf{w}} \quad . \quad (8)$$

The adaptive array cancellation ratio, denoted  $C$ , is defined here as the ratio of the summation of probe-received power after adaptation to the summation of probe-received power before adaptation; that is,

$$C = \frac{p_a}{p_q} \quad . \quad (9)$$

Substituting Equation (7) in Equation (9) yields

$$C = \frac{\mathbf{w}_a^\dagger \mathbf{R} \mathbf{w}_a}{\mathbf{w}_q^\dagger \mathbf{R} \mathbf{w}_q} \quad (10)$$

Next, the covariance matrix defined by the elements in Equations (2) or (3) is Hermitian (that is,  $\mathbf{R} = \mathbf{R}^\dagger$ ), which, by the spectral theorem, can be decomposed in eigenspace [42] as

$$\mathbf{R} = \sum_{k=1}^M \lambda_k \mathbf{e}_k \mathbf{e}_k^\dagger, \quad (11)$$

where  $\lambda_k, k = 1, 2, \dots, M$  are the eigenvalues of  $\mathbf{R}$ , and  $\mathbf{e}_k, k = 1, 2, \dots, M$  are the associated eigenvectors of  $\mathbf{R}$ . The interference covariance matrix eigenvalues ( $\lambda_1, \lambda_2, \dots, \lambda_M$ ) are a convenient quantitative measure of the use of the adaptive array degrees of freedom [43]. The amplitude spread between the largest and smallest eigenvalues is a quantitative measure of the dynamic range of the interference (hot spot) signals.

### 2.2.2 Gradient Search Algorithm

Under conditions where only the probe-received voltage amplitude is measured (as in the BSD-2000 system previously mentioned), it is appropriate to consider a gradient search algorithm to minimize the interference power at selected positions. The gradient search is used to iteratively control the transmit weights so that the RF signal received by the probe array is minimized. The transmit array weights (gain and phase) are adaptively changed in small increments and the probe array output power is monitored to determine weight settings that reduce the output power most rapidly to a null. The mathematical formulation for the gradient search is developed in a straightforward manner [44] and will not be considered further here. Only the sample covariance matrix inversion algorithm has been implemented in the focused near-field nulling simulation presented in this report.

## 2.3 MOMENT-METHOD FORMULATION

This section describes a method of moments formulation to compute the probe-received voltages in Equation (2) due to the transmitting hyperthermia phased-array antenna in an infinite homogeneous conducting medium. The medium is described by the three parameters  $\mu, \epsilon$ , and  $\sigma$ , which are discussed in the next section. The formulation given here is analogous to that developed under array-receiving conditions for an adaptive radar [29]. The software used to analyze a hyperthermia array is based on the receive-array analogy but the theory presented below is given in the context of a transmit array. Referring to Figure 9, assume that each transmit element is fed with a generator having a known impedance  $Z_L$ . Let  $v_{n,j}^{o.c.}$  represent the open-circuit voltage at the  $j$ th probe due to the  $n$ th transmit-array element. Here, the  $j$ th probe can denote either the focal point calibration probe or one of the auxiliary probes used to null a sidelobe. The number of auxiliary probes is denoted by  $J_{aux}$ . The receive probe is assumed to be terminated in an impedance  $Z_r$ .

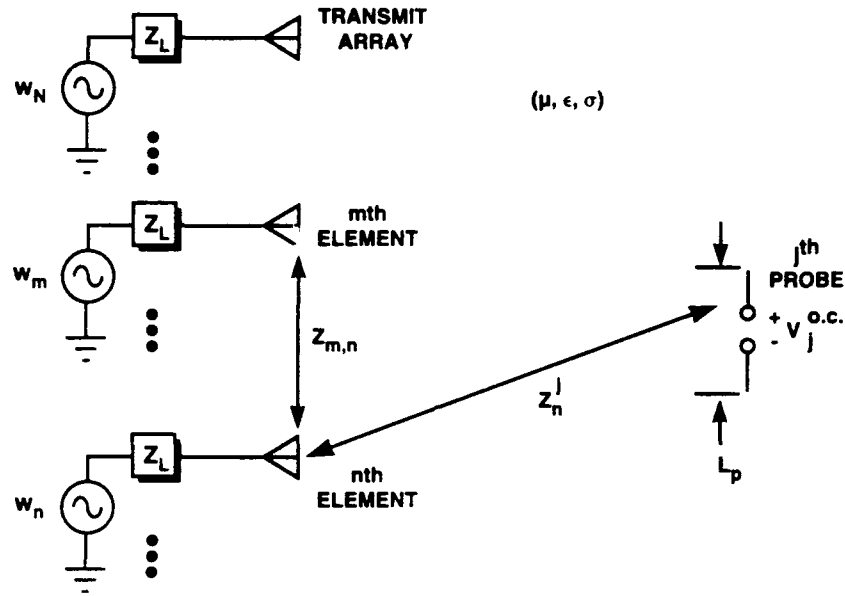


Figure 9. Transmit array and receive antenna probe. Open-circuit mutual impedance between array elements is denoted  $Z_{m,n}$ . The open-circuit voltage at the probe is computed from the array terminal currents and from  $Z_n^j$ , the open-circuit mutual impedance between the nth array element and the jth probe antenna.

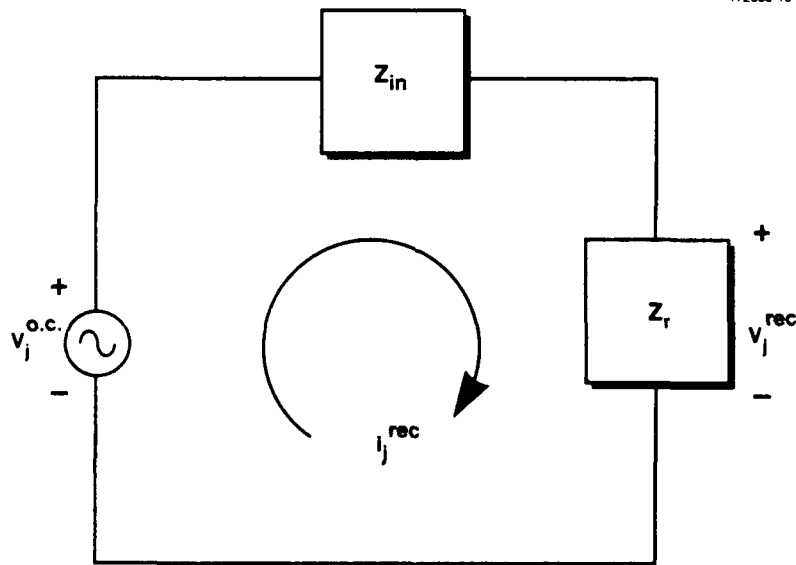


Figure 10. Equivalent circuit model for receive antenna probe.

Next, let  $\mathbf{Z}$  denote the open-circuit mutual impedance matrix (with dimensions  $N \times N$  for the  $N$ -element array). The open-circuit mutual impedance between array elements  $m$  and  $n$  is denoted  $Z_{m,n}$ . It is assumed that multiple interaction between the hyperthermia array and the probe sensor can be neglected. Thus, the hyperthermia array terminal current vector  $\mathbf{i}$  can be computed in terms of the transmit weights  $\mathbf{w}$  as

$$\mathbf{i} = [\mathbf{Z} + \mathbf{Z}_L \mathbf{I}]^{-1} \mathbf{w} \quad (12)$$

Next, let  $Z_n^j$  be the open-circuit mutual impedance between the  $j$ th probe and the  $n$ th array element. The induced open-circuit voltage  $v_{n,j}^{o.c.}$  at the  $j$ th receive probe, due to the  $n$ th array element transmit current  $i_n$ , can then be expressed as

$$v_{n,j}^{o.c.} = Z_n^j \cdot i_n \quad (13)$$

In matrix form, the induced open-circuit probe-voltage matrix  $\mathbf{v}_{probe}^{o.c.}$  is

$$\mathbf{v}_{probe}^{o.c.} = \mathbf{Z}_{probe,array} \mathbf{i} \quad (14)$$

or

$$\mathbf{v}_{probe}^{o.c.} = \mathbf{Z}_{probe,array} [\mathbf{Z} + \mathbf{Z}_L \mathbf{I}]^{-1} \mathbf{w} \quad (15)$$

where  $\mathbf{Z}_{probe,array}$  is a rectangular matrix of order  $J_{aux} \times N$  for the open-circuit mutual impedance between the probe array and the hyperthermia array. Note: the  $j$ th row of the matrix  $\mathbf{Z}_{probe,array}$  is written as  $(Z_1^j, Z_2^j, \dots, Z_N^j)$ , where  $j = 1, 2, \dots, J_{aux}$ . The receive voltage matrix is then computed by the receiving circuit equivalence theorem for an antenna [50]. The receive-antenna equivalent circuit is depicted in Figure 10, where it is readily determined that

$$v_{probe}^{rec} = v_{probe}^{o.c.} \frac{Z_r}{Z_{in} + Z_r} \quad (16)$$

where  $Z_{in}$  is the input impedance of the probe. It should be noted that the  $\mathbf{v}_{probe}^{rec}$  matrix is a column vector of length  $J_{aux}$  and  $v_j^{rec}$  is the  $j$ th element of the matrix. The probe-receive current matrix is given by

$$\mathbf{i}_{probe}^{rec} = \mathbf{v}_{probe}^{o.c.} \frac{1}{Z_{in} + Z_r} \quad (17)$$

The  $j$ th element of the column vector  $i_{probe}^{rec}$  is denoted  $i_j^{rec}$ ,  $j = 1, 2, \dots, J_{aux}$ . Finally, the power received by the  $j$ th probe is

$$p_j^{rec} = \frac{1}{2} Re(v_j^{rec} \cdot i_j^{rec*}) \quad , \quad (18)$$

where  $Re$  means real part. Substituting Equations (16) and (17) into Equation (18) yields

$$p_j^{rec} = \frac{1}{2} |v_j^{o.c.}|^2 \frac{Re(Z_r)}{|Z_{in} + Z_r|^2} \quad . \quad (19)$$

The total interference power received by the auxiliary probe array is given by

$$p^{rec} = \sum_{j=1}^{J_{aux}} p_j^{rec} \quad . \quad (20)$$

The incident electric field  $E$  is related to the open-circuit voltage  $v^{o.c.}$  by the effective height  $h$  of the probe antenna [48] as

$$v^{o.c.} = hE \quad . \quad (21)$$

If the length  $L_p$  of the probe antenna is approximately  $0.1\lambda$  or less, the current distribution is triangular and the effective height is  $h = 0.5L_p$  [48]. Thus, for a short-dipole probe the open-circuit voltage can be expressed as

$$v^{o.c.} = \frac{L_p}{2} E \quad . \quad (22)$$

It then follows from Equation (22) that the  $E$  field for a short-dipole probe at position  $(x, y, z)$  is given by

$$E(x, y, z) = \frac{2v^{o.c.}(x, y, z)}{L_p} \quad . \quad (23)$$

Finally, the quiescent and adapted E-field radiation patterns are computed using the quiescent and adapted weight vectors  $w_q$  and  $w_a$ , respectively, in Equations (15) and (23).

The moment-method expansion and testing functions are assumed to be sinusoidal. The open-circuit mutual impedances in Equation (15) between thin-wire dipoles in a homogeneous conducting



medium are computed based on subroutines from a well-known moment-method computer code [38]. In evaluating  $Z_n^j$  for the  $j$ th auxiliary probe, double precision computations are used.

As mentioned previously, the array is calibrated (phased focused) initially using a short dipole at the focal point. To accomplish this numerically, having computed  $\mathbf{v}_{focus}^{rec}$ , the receive array weight vector  $\mathbf{w}$  will have its phase commands set equal to the conjugate of the corresponding phases in  $\mathbf{v}_{focus}^{rec}$ . Transmit antenna radiation patterns are obtained by scanning (moving) a dipole probe with half-length  $l$  in the near-field and computing the receive probe-voltage response.

The received voltage matrix for the  $j$ th probe (denoted  $\mathbf{v}_j^{rec}$ ) is computed at  $K$  frequencies across the nulling bandwidth. Thus,  $\mathbf{v}_j^{rec}(f_1), \mathbf{v}_j^{rec}(f_2), \dots, \mathbf{v}_j^{rec}(f_K)$  are needed. In this report, the impedance matrix is computed at  $K$  frequencies and is inverted  $K$  times. The probe covariance matrix elements are computed by evaluating Equation (2) numerically, using Simpson's rule numerical integration. For multiple auxiliary probes, the covariance matrix is evaluated using Equation (3). Adaptive array radiation patterns are computed by superimposing the quiescent radiation pattern with the weighted sum of auxiliary-channel-received voltages.

### 2.3.1 WAVE PROPAGATION IN CONDUCTING MEDIA

To gain insight into the effect of a lossy medium on the propagation of an electromagnetic wave, it is useful to review certain fundamental equations which govern the field characteristics. In a conducting medium, Maxwell's curl equations in time-harmonic form are

$$\nabla \times \mathbf{H} = \mathbf{J} + j\omega\epsilon\mathbf{E} \quad (24)$$

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H} \quad , \quad (25)$$

where  $\mathbf{E}$  and  $\mathbf{H}$  are the electric and magnetic fields, respectively.  $\mathbf{J}$  is the conduction current density,  $\omega = 2\pi f$  is the radian frequency,  $\epsilon$  is the permittivity of the medium, and  $\mu$  is the permeability of the medium. The permittivity is expressed as  $\epsilon = \epsilon_r\epsilon_o$ , where  $\epsilon_r$  is the dielectric constant (relative permittivity) and  $\epsilon_o$  is the permittivity of free space. Similarly,  $\mu = \mu_r\mu_o$ , where  $\mu_r$  is the relative permeability and  $\mu_o$  is the permeability of free space. For a medium with electrical conductivity  $\sigma$ ,  $\mathbf{J}$  and  $\mathbf{E}$  are related as

$$\mathbf{J} = \sigma\mathbf{E} \quad . \quad (26)$$

Substituting Equation (26) into Equation (24) yields

$$\nabla \times \mathbf{H} = (\sigma + j\omega\epsilon)\mathbf{E} \quad . \quad (27)$$

From Equations (24) and (25), the vector wave equation in terms of  $\mathbf{E}$  is derived as

$$\nabla^2 \mathbf{E} - \gamma^2 \mathbf{E} = 0 \quad . \quad (28)$$

It is readily shown [49] that

$$\gamma = \pm \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} = \pm j\omega\sqrt{\mu\epsilon} \sqrt{1 - j\frac{\sigma}{\omega\epsilon}} \quad . \quad (29)$$

The quantity  $\sigma/\omega\epsilon$  is referred to as the loss tangent. It is common to express the complex propagation constant as

$$\gamma = \alpha + j\beta \quad , \quad (30)$$

where  $\alpha$  is the attenuation constant and  $\beta$  is the phase constant. The constants  $\alpha$  and  $\beta$  are found by setting Equation (29) equal to Equation (30) and then squaring both sides, equating the real and imaginary parts, and solving the pair of simultaneous equations, with the result

$$\alpha = \frac{\omega\sqrt{\mu\epsilon}}{\sqrt{2}} \left\{ \sqrt{1 + \left(\frac{\sigma}{\omega\epsilon}\right)^2} - 1 \right\}^{1/2} \quad (31)$$

$$\beta = \frac{\omega\sqrt{\mu\epsilon}}{\sqrt{2}} \left\{ \sqrt{1 + \left(\frac{\sigma}{\omega\epsilon}\right)^2} + 1 \right\}^{1/2} \quad . \quad (32)$$

The wavelength  $\lambda$  in the lossy dielectric is then computed from

$$\lambda = \frac{2\pi}{\beta} \quad . \quad (33)$$

The intrinsic wave impedance  $\eta$  is given by

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} = \sqrt{\frac{\mu}{\epsilon}} \frac{1}{\sqrt{1 - j\frac{\sigma}{\omega\epsilon}}} \quad . \quad (34)$$

The instantaneous power density of the electromagnetic field is given by Poynting's vector, denoted  $\mathbf{P}$ .

$$\mathbf{P} = \frac{1}{2} \mathbf{E} \times \mathbf{H}^* \quad , \quad (35)$$

which has units of (W/m<sup>2</sup>). The time-average power flow density is equal to the real part of the complex Poynting's vector. The time-average power dissipation per unit volume  $P_d$  (W/m<sup>3</sup>) is derived from Maxwell's equations, with the result

$$P_d = \frac{1}{2} \mathbf{E} \cdot \mathbf{J}^* = \frac{1}{2} \sigma |\mathbf{E}|^2 \quad . \quad (36)$$

The specific absorption rate (SAR) [2] is the power dissipated or absorbed per unit mass (W/kg) of the medium (tissue), or

$$SAR = \frac{P_d}{\rho} = \frac{\sigma}{2\rho} |\mathbf{E}|^2 \quad , \quad (37)$$

where  $\rho$  is the density of the medium in kg/m<sup>3</sup>.

It is convenient to have a simple equation for computing the propagation loss between any two points in the near field of an isolated transmitting antenna. Thus, mutual coupling effects are ignored for the time being. Consider a time-harmonic source radiating a spherical wave into an infinite homogeneous conducting medium. For an isotropic radiator, and suppressing the  $e^{j\omega t}$  time dependence, the electric field as a function of range  $r$  can be expressed as

$$E(r) = E_o \frac{e^{-\gamma r}}{r} \quad , \quad (38)$$

where  $E_o$  is a constant.

For a source at the origin, the amplitude of the electric field at range  $r_1$  is given by

$$|E(r_1)| = E_o \frac{e^{-\alpha r_1}}{r_1} \quad , \quad (39)$$

and at range  $r_2$  by

$$|E(r_2)| = E_o \frac{e^{-\alpha r_2}}{r_2} \quad . \quad (40)$$

The total propagation loss between ranges  $r_1$  and  $r_2$  is found by taking the ratio of Equations (40) and (39), or

$$\frac{|E(r_2)|}{|E(r_1)|} = \frac{r_1}{r_2} e^{-\alpha(r_2-r_1)} \quad . \quad (41)$$

The field attenuation  $A_\alpha$  in dB from range  $r_1$  to range  $r_2$  due to the lossy dielectric is simply

$$A_\alpha = 20 \log_{10}(e^{-\alpha(r_2-r_1)}) \quad (42)$$

Similarly, the  $1/r$  attenuation loss  $A_r$  in dB is

$$A_r = 20 \log_{10} \frac{r_1}{r_2} \quad (43)$$

### 2.3.2 THERMAL MODELING OF AN INHOMOGENEOUS TARGET

A thermal analysis computer program called the transient thermal analyzer (TTA), developed by Arthur D. Little, Inc., has been used at Lincoln Laboratory for space payload analysis since 1969. Recent documentation for TTA exists [51,52]. The important details of the analysis are described in this section. The TTA software is used in the next section to accomplish the thermal modeling of homogeneous muscle tissue surrounded by a constant-temperature water bolus. Thermal modeling techniques have been described in detail [53].

The TTA program uses the finite-difference technique to solve a set of nonlinear energy balance equations. Consider a system of interconnected nodes that model an inhomogeneous volume for which the temperature  $T_i$  of the  $i$ th node is to be determined. The heat-balance equation, which is solved by TTA, is expressed as

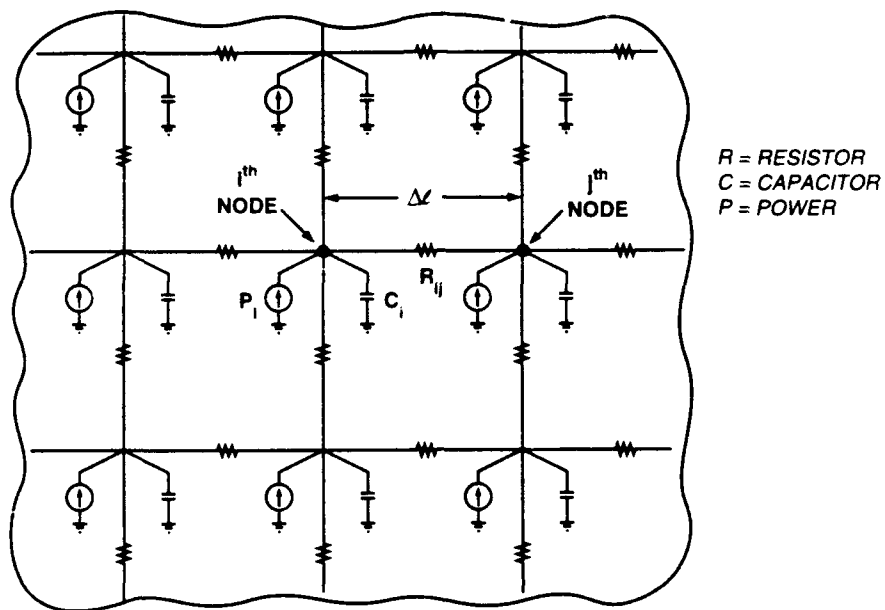
$$\sum_{j=1}^N Q_{i,j} - P_i(t) + M_i \frac{dT_i}{dt} = 0 \quad , \quad (44)$$

where  $Q_{i,j}$  is the net outward heat flow from node  $i$  in the direction of node  $j$ ,  $P_i(t)$  is the power into node  $i$  at time  $t$ , and  $M_i$  is the thermal mass (mass times specific heat) of node  $i$ . Figure 11 shows an electric circuit analog which is used to model the two-dimensional thermal characteristics of the material volume. Power  $P_i$  in watts is delivered to the  $i$ th node. Capacitor  $C_i$  (with units Joules/ $^{\circ}$ C) is used to model the thermal capacitance at the  $i$ th node. Resistor  $R_{i,j}$  (with units  $^{\circ}$ C/W) is used to model the heat resistance between nodes  $i$  and  $j$ .

With a spacing of  $\Delta l$  between nodes (assuming cubic cells), the values of  $R_{i,j}$ ,  $C_i$  and  $P_i$  are computed as

$$R_{i,j} = \frac{1}{k_{i,j} \Delta l} \quad , \quad (45)$$

where  $k_{i,j}$  is the thermal conductivity (with units W/ $m^{\circ}$ C) between nodes  $i$  and  $j$ ;



$$R = \frac{1}{k\Delta l} [^{\circ}\text{C} / \text{W}], k = \text{THERMAL CONDUCTIVITY}$$

$$C = \rho C_p (\Delta l)^3 [\text{J}/^{\circ}\text{C}], \rho = \text{DENSITY}, C_p = \text{SPECIFIC HEAT}$$

$$P = \text{SAR } \rho (\Delta l)^3 [\text{W}], \text{SAR} = \frac{\sigma}{2\rho} |E|^2 (\text{Specific Absorption Rate})$$

$$\sigma = \text{ELECTRICAL CONDUCTIVITY}$$

$$|E| = \text{MAGNITUDE OF ELECTRIC FIELD}$$

Figure 11. Equivalent circuit model used in thermal analysis. The inhomogeneous body of interest is modeled with a grid of nodes interconnected by resistors. Each node has an associated power source and capacitor.

$$C_i = \rho_i C_{pi} (\Delta l)^3 \quad , \quad (46)$$

where  $C_{pi}$  is the specific heat at the  $i$ th node and  $\rho_i$  is the density ( $\text{kg/m}^3$ ) at the  $i$ th node; and

$$P_i = (SAR)_i \rho_i (\Delta l)^3 \quad , \quad (47)$$

where  $(SAR)_i$  is the SAR for the  $i$ th node, which is given by

$$(SAR)_i = \frac{\sigma_i}{2\rho_i} |E_i|^2 \quad , \quad (48)$$

where  $\sigma_i$  is the electrical conductivity of the  $i$ th node and  $|E_i|$  is the magnitude of the electric field delivered by the hyperthermia array to the  $i$ th node. Note: in substituting Equation (48) into Equation (47), the density  $\rho_i$  cancels. Thus, an equivalent approach to computing the power delivered to the  $i$ th node is written in terms of the time-average power dissipated per unit volume of the  $i$ th node (denoted  $P_{di}$ ) as

$$P_i = P_{di} (\Delta l)^3 \quad . \quad (49)$$

A block diagram showing how TTA is used in the hyperthermia analysis is given in Figure 12. First, the method of moments, controlled by the SMI nulling algorithm, is used to compute the electric field radiation pattern throughout a homogeneous region (muscle tissue). This power distribution is then read into the TTA program, which computes the temperature distribution inside an elliptical muscle-tissue target surrounded with a constant-temperature water bolus.

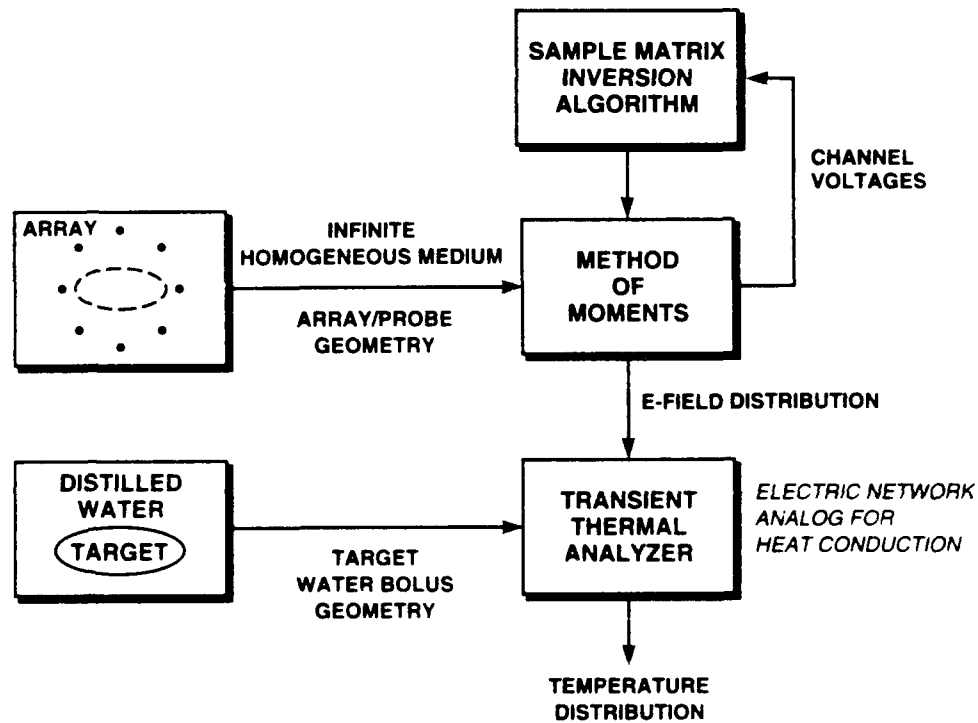


Figure 12. The moment-method simulation's use with the transient thermal analysis. RF power distribution over the target region is converted into a time-dependent temperature distribution.

### 3. SIMULATION RESULTS

To demonstrate the effectiveness of focused near-field adaptive nulling in reducing undesired hot spots, several computer simulations are presented. The E-field simulations are for the signal received by a short-dipole probe due to a transmitting phased array embedded in an infinite homogeneous lossy dielectric (muscle tissue). However, the thermal simulations are for an elliptical target (muscle tissue) surrounded by a constant-temperature water bolus. Because the RF wavelengths in the target and water bolus are similar, the E-field simulations are believed to give a reasonable approximation to the field distribution inside the elliptical target.

The E-field calculation in the assumed infinite homogeneous medium introduces additional field attenuation not present in a clinical hyperthermia system with an annular array transmitting through a water bolus into a patient. (As mentioned earlier, the water bolus has very little RF propagation loss.) In addition, the transmit array weights are normalized according to Equation (6). Thus, in this report no attempt is made to compute the absolute E-field strength in volts/meter in the elliptical target. Instead, the peak power in the elliptical target is adjusted (by a scale factor) to produce a desired maximum focal-region temperature ( $T_{max}$ ) after  $t$  minutes. Note: an approximate absolute scale factor could be computed by making an initial computer simulation with an infinite homogeneous water bolus and then matching the target boundary field to the infinite homogeneous muscle tissue simulation.

The computer simulation model is related, in part, to the hyperthermia annular phased-array antenna system shown in Figure 1. This hyperthermia system uses a 60-cm array diameter with eight uniformly spaced dipole elements (fed as four pairs) which operate over the frequency band 60-120 MHz [21]. The simulated array is assumed to be fully adaptive, and with eight adaptive elements seven independent nulls can be formed while simultaneously focusing on a tumor. For comparison, the BSD-2000 hyperthermia system could be used to form up to three independent nulls.

In this section, we assume that the adaptive radiation pattern null-width characteristics in a homogeneous target will be similar to the characteristics observed in an inhomogeneous target. The null width is directly related to the wavelength and there is only a 5 percent change in wavelength between the assumed muscle tissue and water bolus. With this assumption, the transmit array is embedded in homogeneous tissue, which allows direct use of the thin-wire moment-method formulation in Section 2.3. After computing the two-dimensional electric-field distribution in the homogeneous medium, we then consider only an elliptical portion of the homogeneous region and use the ellipse as the homogeneous target. In the thermal analysis, the elliptical target is surrounded with a constant 10°C water bolus. The electric field amplitude is scaled to produce a 46°C peak temperature, at time  $t = 20$  minutes, at the center of the elliptical phantom. The initial temperature of the phantom is assumed to be 25°C (room temperature).

All computer simulations presented in this section are at a 120-MHz operating frequency with four auxiliary nulling sensors; that is,  $N_{aux} = 4$ . Degraded system performance due to an



insufficient number of auxiliary probes is considered in Appendix A. The parameters used in the electrical and thermal analyses are summarized in Table 1. These parameters, obtained in part

**TABLE 1**  
**Parameters Used in Electrical/Thermal Analysis**

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PARAMETER	PHANTOM MUSCLE TISSUE	DISTILLED WATER
DIELECTRIC CONSTANT @ 100 MHz	73.5	80.0
ELECTRICAL CONDUCTIVITY @ 100 MHz	0.5 S/m	0.0001 S/m
DENSITY	970.0 kg/m <sup>3</sup>	1000.0 kg/m <sup>3</sup>
SPECIFIC HEAT	3516.0 J/kg °C	4200.0 J/kg °C
THERMAL CONDUCTIVITY	0.544 W/m °C	0.6019 W/m °C

from Sullivan [9], are for a frequency of 100 MHz; we assume that similar values of the parameters will exist at 120 MHz. Notice that the relative dielectric constants of phantom muscle tissue and distilled water are very similar; however, the electrical conductivities are vastly different. The relevant thermal characteristics—density, specific heat, and thermal conductivity [35]—are very similar for phantom muscle tissue and distilled water.

### 3.1 ELECTRIC FIELD FOR ARRAY IN HOMOGENEOUS TISSUE

Substituting the values  $f = 120$  MHz,  $\sigma = 0.5$  S/m, and  $\epsilon_r = 73.5$  into Equation (29) yields  $\gamma_m = 10.0 + j23.8$  for the muscle tissue. With  $\beta_m = 23.8$  radians/m, the wavelength in

the phantom muscle tissue is  $\lambda_m = 26.5$  cm. The attenuation constant for the muscle tissue is  $\alpha_m = 10.0$  radians/m. Similarly, for distilled water  $\gamma_w = 0.0021 + j22.5$ , so the wavelength is  $\lambda_w = 27.9$  cm. The attenuation constant for the distilled water medium is  $\alpha_w = 0.0021$  radians/m. The propagation loss in the phantom muscle tissue is  $20 \log_{10} e^{-10.0}$ , or  $-0.87$  dB/cm. Similarly, the propagation loss in the distilled water is found to be  $-0.0002$  dB/cm. Thus, the total loss due to propagation through 15 cm of distilled water is 0.003 dB. For 15 cm of muscle tissue the corresponding loss is 13.1 dB. The wave impedance in the muscle tissue is computed from Equation (34) as  $\eta_m = 33.9 + j 14.2 \Omega$ , and similarly in the distilled water  $\eta_w = 42.1 + j 0.004 \Omega$ .

The geometry used in the simulations is shown in Figure 13. A 60-cm-diameter ring array of eight dipoles uniformly surrounds a fictitious elliptical target zone with major axis 30 cm and minor axis 20 cm. The length of each perfectly conducting center-fed dipole array element at 120 MHz in the infinite homogeneous muscle tissue is  $\lambda/2$ , or 13.25 cm. The array focus is assumed at the origin, and four auxiliary short-dipole sensors with length 1.27 cm ( $0.05\lambda$ ) are positioned in  $(x, y, z)$  coordinates at (15 cm, 0, 0), (-15 cm, 0, 0), (0, 0, 10 cm), and (0, 0, -10 cm); that is, the auxiliary E-field sensors are located every  $90^\circ$  in azimuth on the perimeter of the target. In rectangular coordinates, each dipole is oriented in the  $\hat{y}$  direction and the feed terminals of each dipole are located at  $y = 0$ . The moment-method computer simulations were run on a Sun 3/260 workstation. The total CPU time for a complete moment-method run is 19.2 minutes. This CPU time includes computing the quiescent and adaptive radiation patterns on a 41 by 41 grid of points. The CPU time without radiation pattern calculations is 33 seconds.

The two-dimensional radiation pattern in the plane  $y = 0$ , before nulling, at 120 MHz with uniform amplitude and phase illumination, is shown in Figure 14. The calculated data are collected on a 41 by 41 grid of points over a square region, with side length 76.2 cm, centered at the focus. The spacing between data points is 1.905 cm, or  $0.072\lambda$ , and the contour levels are displayed in 10-dB steps. The E-field data are computed for the case of a 1.27-cm short-dipole observation probe. The positions of the eight dipole radiators are clearly evident by the  $-20$ -dB contours surrounding each element. The radiation pattern is symmetric because of the symmetry of the array and the assumed homogeneous medium.

Finer contour levels (1-dB steps) for the quiescent radiation pattern are displayed in Figure 15. Here, it is evident that the focused main beam of the ring array is increasing in amplitude as the observation point moves closer to the focus. Away from the main beam region, the pattern amplitude is seen to increase as the observation position moves away from the focus.

A quiescent radiation pattern cut at  $z = 0$  is shown in Figure 16. The large amplitude that occurs at  $\pm 30$  cm is due to the E-field probe's close proximity to the transmitting elements. The large attenuation that occurs from the array diameter to the focus is due to the  $1/r$  attenuation loss and the loss in the uniform homogeneous muscle tissue. The radiation pattern cut for  $x = 0$  in Figure 17 is identical to the pattern in Figure 16 due to the symmetry of the array. In both Figures 16 and 17 the boundary of the fictitious elliptical target zone is indicated. The increasing radiation pattern amplitude near the left and right sides of the elliptical target (Figure 16) will be

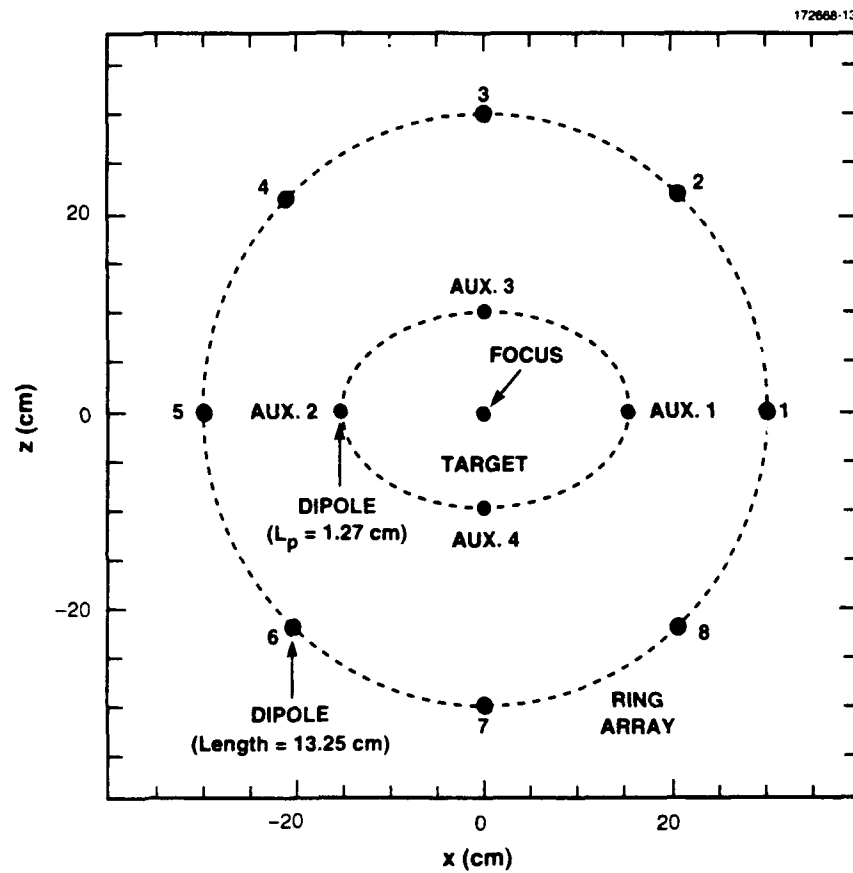


Figure 13. Geometry for eight-element ring array and four  $E$ -field auxiliary sensors.

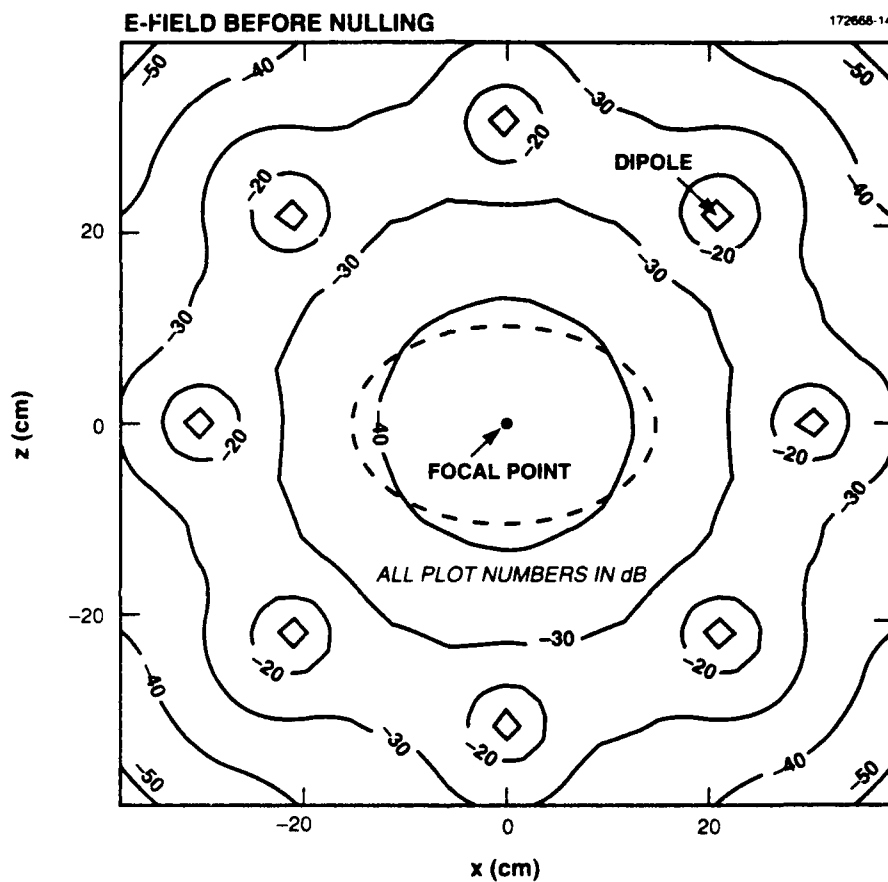


Figure 14. Simulated two-dimensional quiescent radiation pattern at 120 MHz for uniformly illuminated eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue:  $\epsilon_r = 73.5$ ,  $\sigma = 0.5$ ). A fictitious elliptical target region is indicated by the dashed curve. Radiation contour levels are in 10-dB steps.

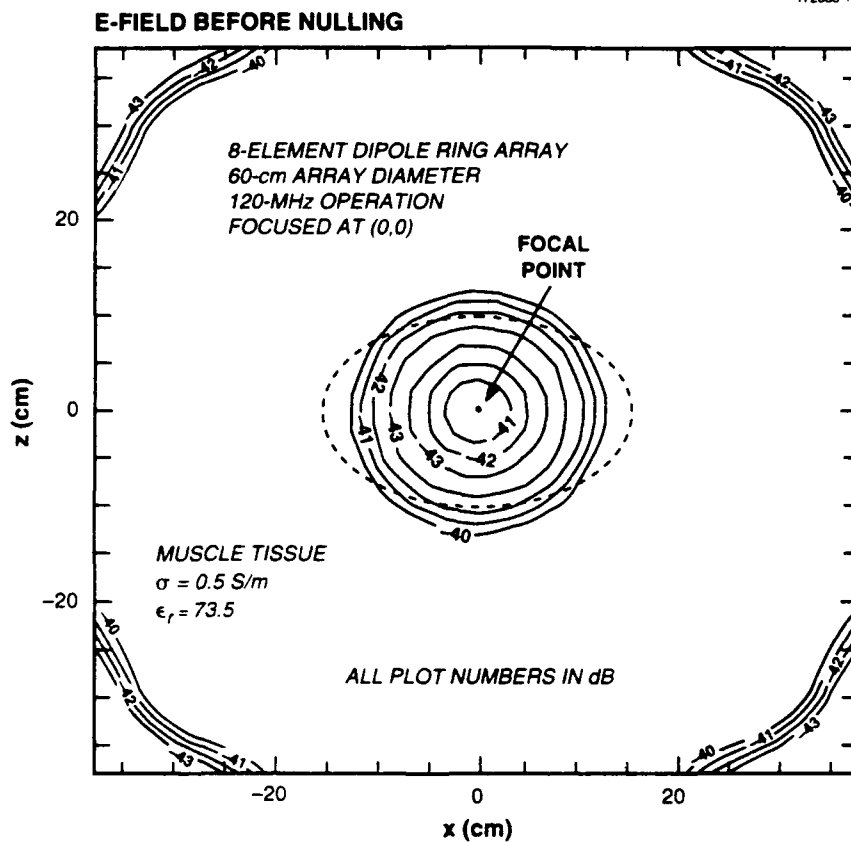


Figure 15. Simulated two-dimensional quiescent radiation pattern at 120 MHz for uniformly illuminated eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue:  $\epsilon_r = 73.5$ ,  $\sigma = 0.5$ ). A fictitious elliptical target region is indicated by the dashed curve. Radiation contour levels are given in 1-dB steps.

shown to produce hot spots in the thermal distribution. As shown in the next section, because the top (anterior) and bottom (posterior) of the elliptical target are not as strongly illuminated as the left and right sides, no quiescent hot spots occur at the top or bottom. From Figure 16, the

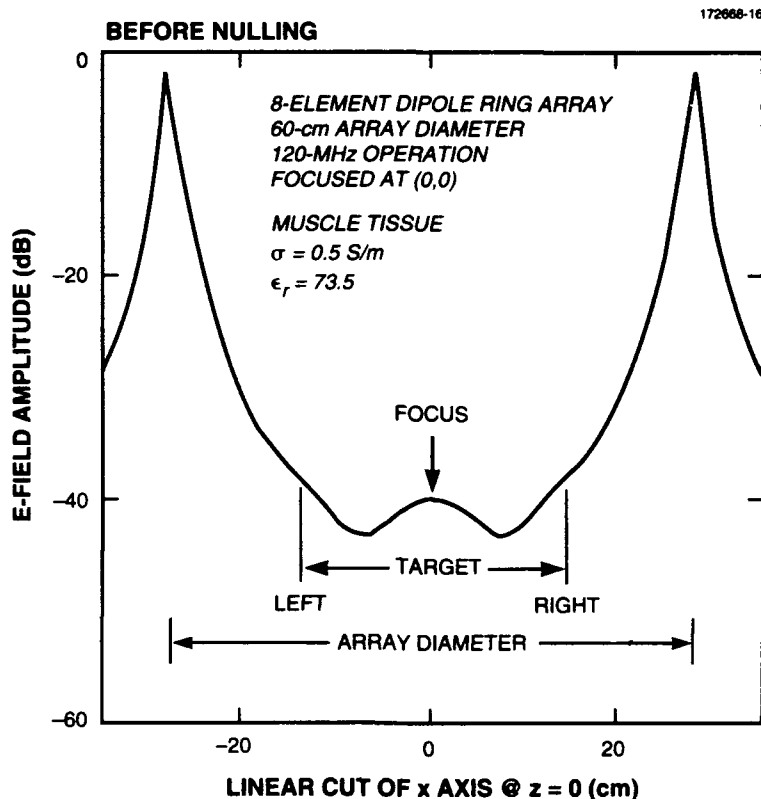


Figure 16. Simulated one-dimensional quiescent radiation pattern cut ( $z = 0$ ) at 120 MHz for uniformly illuminated eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue:  $\epsilon_r = 73.5$ ,  $\sigma = 0.5$ ).

ring-array half-power beamwidth in the target region is approximately 13 cm, or approximately one-half the wavelength (26.5 cm) in the phantom muscle tissue.<sup>2</sup> The adaptive nulling resolution

<sup>2</sup>Sullivan [54] has recently published simulations and measurements of SAR patterns at 70–110 MHz, using a homogeneous 35 × 25-cm elliptical target surrounded with a layer of fat and a water

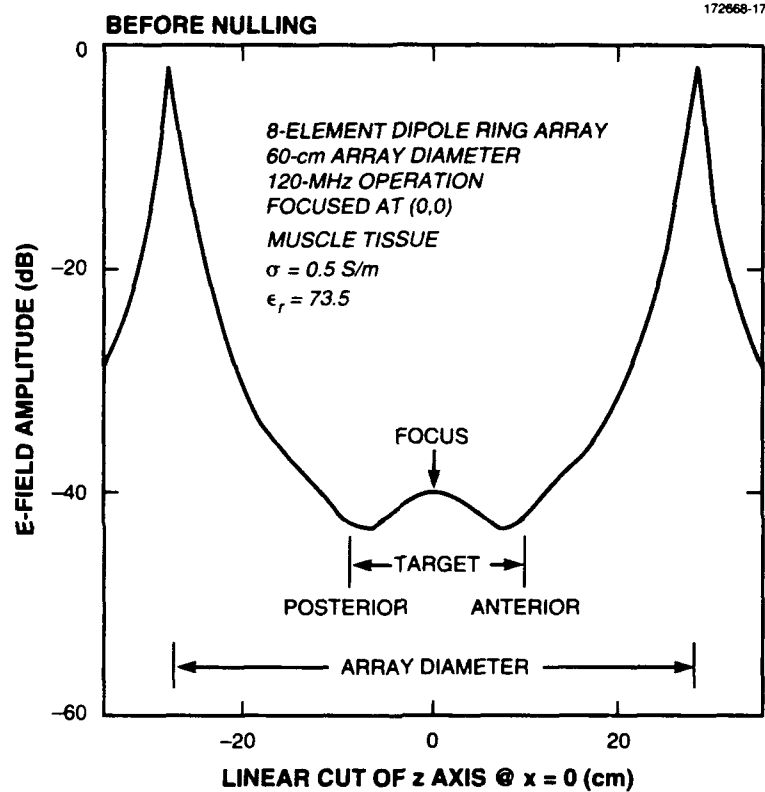


Figure 17. Simulated one-dimensional quiescent radiation pattern cut ( $x = 0$ ) at 120 MHz for uniformly illuminated eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue:  $\epsilon_r = 73.5$ ,  $\sigma = 0.5$ ).

or closest allowed spacing between a deep adaptive null and the main beam is equal to the half-power beamwidth of the antenna [55]. Thus, the closest allowed null position is 13 cm from the focus. Since the target width is 30 cm, two nulls can be formed at  $(x = \pm 15 \text{ cm}, z = 0)$  without disturbing the focus. However, if two deep nulls are formed at  $(x = 0, z = \pm 10 \text{ cm})$  the focus will be compromised. In practice, the water bolus would restrict the placement of short-dipole sensors to the surface of the target. Thus, only weak nulls can be formed at  $(x = 0, z = \pm 10 \text{ cm})$  so that the focus will not be affected by the adaptive nulling process.

Next, adaptive radiation patterns are computed with four auxiliary dipole sensors; their positions are shown in Figure 13. The value of the receiving gain for auxiliary dipoles 1 and 2 is adjusted to produce a greater-than-35-dB SNR. This amount of SNR results in greater than 35 dB of nulling in the direction of auxiliary dipoles 1 and 2. In contrast, the gain values for auxiliary dipoles 3 and 4 are turned down to produce about a 3-dB SNR. Thus, only about 3 dB of nulling will occur at sensor positions 3 and 4 as the adaptive algorithm reduces the interference to the noise level of the receiver. The reason for choosing these null depths will become apparent with the data that follow. Figure 18 shows the two-dimensional radiation pattern after nulling with four auxiliary sensors. Two deep adaptive nulls at  $x = \pm 15 \text{ cm}$  occur as expected, and weak nulling occurs at  $z = \pm 10 \text{ cm}$ , also as expected. The two deep nulls in the  $z = 0$  cut are quantified in Figure 19, where greater than 35 dB of interference nulling or pattern reduction occurs at  $x = \pm 15 \text{ cm}$ . The peak level at the focus is adjusted to 0 dB for both the quiescent and adaptive patterns. Two weak adaptive nulls are in effect in the  $x = 0$  radiation pattern cut shown in Figure 20; however, weak nulls are desired in this cut due to temperature considerations, as shown in the next section. The weak nulls in effect in the adaptive patterns reduce variation from the quiescent radiation pattern. Finally, the transmit array weights before and after nulling and the covariance matrix eigenvalues are shown in Figures 21 and 22, respectively. The adaptive transmit weights exhibit a 5-dB dynamic range in Figure 21(a). There are two large eigenvalues and two weak (nonzero) eigenvalues shown in Figure 22. These eigenvalues are directly associated with the two high-SNR auxiliary sensors and the two weak-SNR auxiliary sensors. Note that the 0-dB level in Figure 22 is equal to the noise level. The probe-array output power before and after adaptive nulling is 31.4 dB and 0.9 dB, respectively. This difference in power before and after nulling means that the adaptive cancellation is -30.5 dB. The output file for the moment-method simulation of this section is given in Appendix B.

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bolus. A comparison of Sullivan's 110-MHz SAR simulation (Figure 5(a) of his paper) and the results (at 120 MHz) presented in Figures 16 and 17 of this report indicate reasonable agreement over the elliptical target region.



# E-FIELD AFTER NULLING; 4 AUXILIARIES

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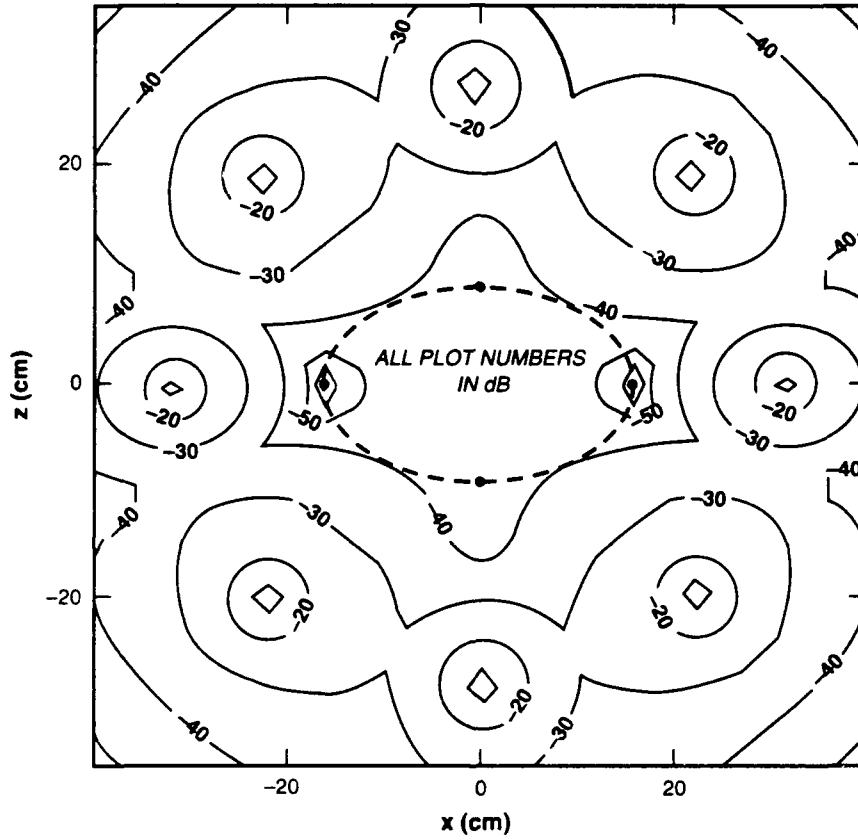


Figure 18. Simulated two-dimensional adaptive radiation pattern at 120 MHz for eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue:  $\epsilon_r = 73.5$ ,  $\sigma = 0.5$ ). Radiation contour levels are given in 10-dB steps. Four auxiliary sensors are used in forming the adaptive pattern. The quiescent focus is at (0,0).

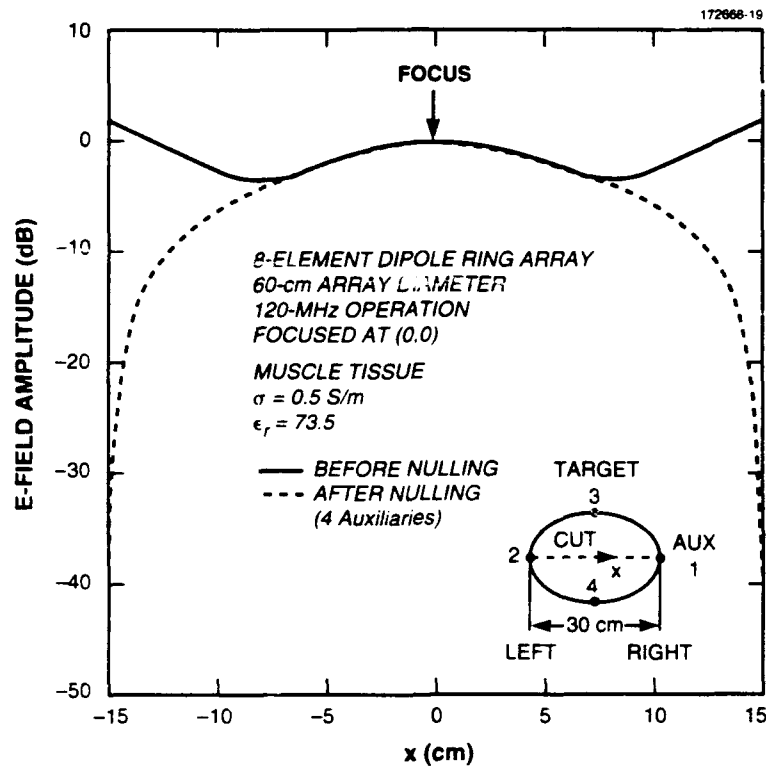


Figure 19. Simulated one-dimensional quiescent and adaptive radiation patterns in the  $z = 0$  cut at 120 MHz for eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue:  $\epsilon_r = 73.5$ ,  $\sigma = 0.5$ ). Four auxiliary sensors are used in forming the adaptive pattern.

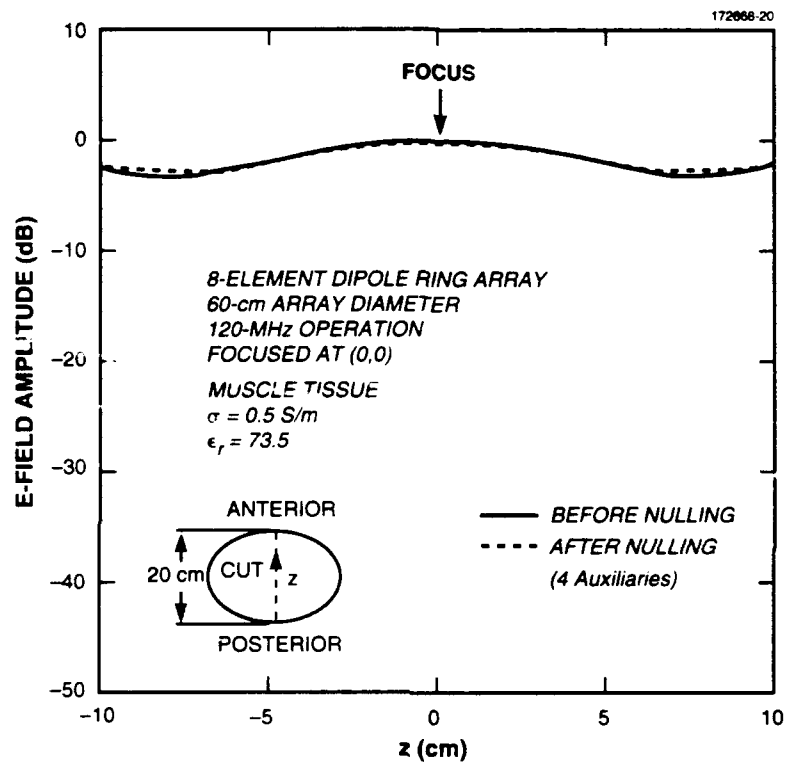


Figure 20. Simulated one-dimensional quiescent and adaptive radiation patterns in the  $x = 0$  cut at 120 MHz for eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue:  $\epsilon_r = 73.5$ ,  $\sigma = 0.5$ ). Four auxiliary sensors are used in forming the adaptive pattern.

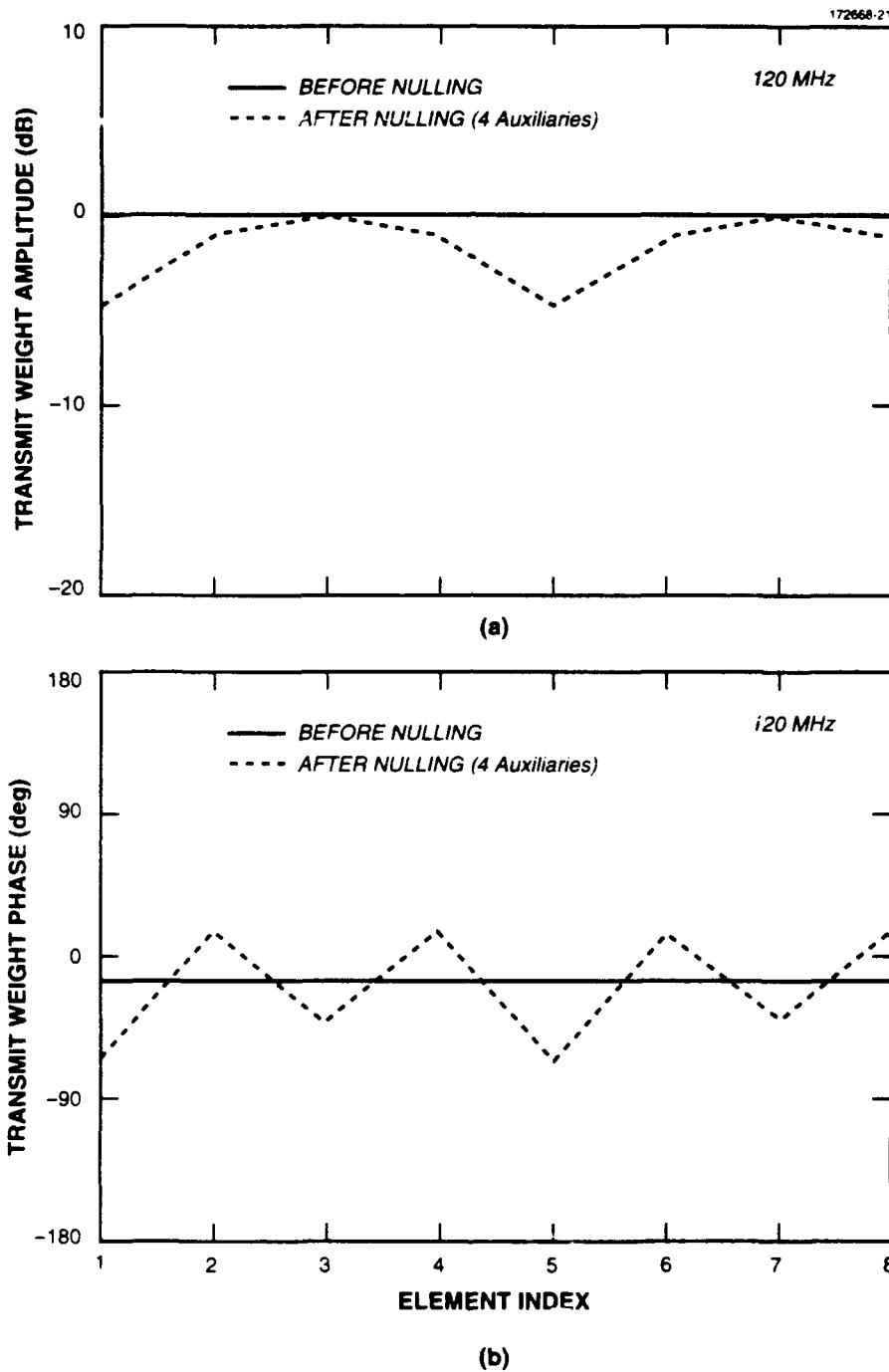


Figure 21. Transmit array weights before and after adaptive nulling. A dynamic range of about 5 dB is evident for the adaptive weights. Four auxiliary sensors are used in the adaptive process. (a) Amplitude; (b) Phase.

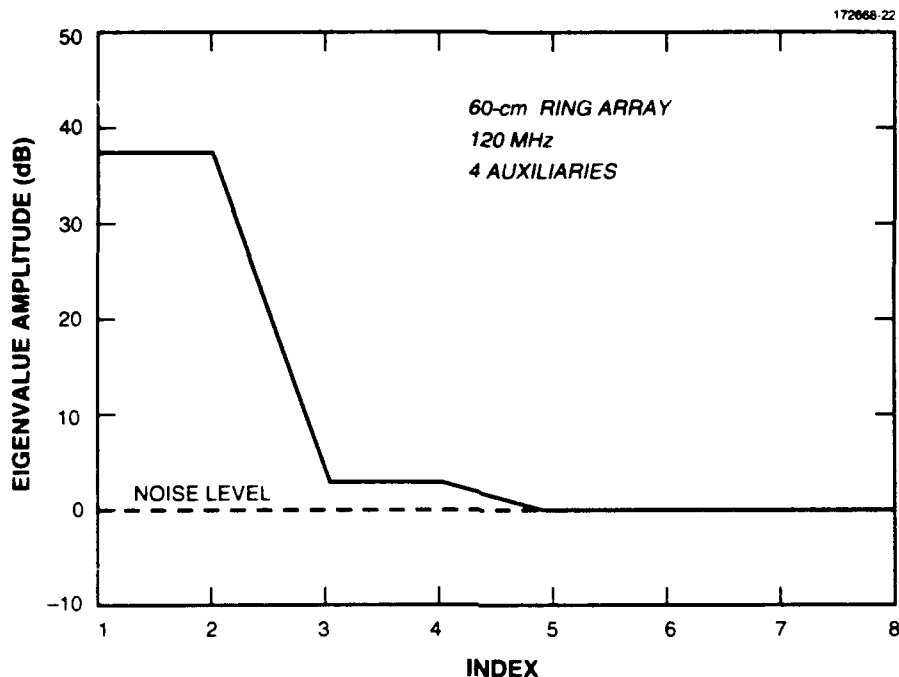


Figure 22. Channel covariance matrix eigenvalues (degrees of freedom) used in the adaptive process with four auxiliary sensors.

## 3.2 TEMPERATURE DISTRIBUTION IN ELLIPTICAL PHANTOM

In this section, the transient thermal analysis software is used to compute the temperature distribution in an elliptical phantom surrounded with a constant-temperature water bolus. The 41 by 41 two-dimensional E-field radiation pattern data from the previous section are used as the power source for the thermal node network. Two spacings of nodes are considered here: initially, the node spacing  $\Delta x = \Delta z = \Delta l = 1.905$  cm (coarse grid) is used; to check convergence, the node spacing is then decreased by a factor of two to  $\Delta l = 0.9525$  cm (fine grid). The coarser spacing is shown to be adequate.

### 3.2.1 1.905-cm Thermal Node Spacing

Note: the scale factors used to convert the normalized E-field distributions to a power level that induces a 46°C peak temperature at  $t = 20$  minutes are 94.1 dB and 96.0 dB for the quiescent and adaptive patterns, respectively. These scale factors are determined by trial and error. From equations given in Section 2.3.2 and the parameter values in Table 1, all resistors in the phantom muscle tissue had a value of 96.5°C/W and all resistors in the water bolus had a value of 87.2°C/W. The value of the capacitors in the phantom muscle tissue is 23.6 J/°C; values for capacitors in the

water-bolus region are not used in the input to the transient thermal analysis software. Instead, a constant temperature of  $10^{\circ}\text{C}$  is enforced at each water-bolus node. With a 41 by 41 grid, a total of 3280 resistors and 1681 capacitors are used in the thermal simulation. The CPU time required to compute the temperature distribution on a 41 by 41 grid is under four minutes.

Figure 23 shows the two-dimensional temperature distribution produced at time  $t = 20$  minutes in the elliptical phantom muscle tissue target without adaptive nulling. To generate Figure 23, the power source used in the transient thermal analysis is the quiescent radiation pattern given in Figure 14. The initial temperature (at time  $t = 0$ ) is  $25^{\circ}\text{C}$ . Notice the occurrence of two hot spots on the left and right sides of the elliptical phantom. The peak temperature on-focus is  $46^{\circ}\text{C}$ , which is achieved by scaling the normalized quiescent E-field as described earlier. The two hot spots are quantified in the  $z = 0$  temperature pattern cut shown in Figure 24. While the peak temperature at each hot spot in Figure 24 is only  $41^{\circ}\text{C}$ , the temperature profile for  $x = 0$  in Figure 25 shows no hot spots. As any undesired hot spot is a potential source for compromising the therapy session, adaptive nulling is used to reduce the sidelobes corresponding to the hot spots.

Figure 26 shows the simulated two-dimensional thermal distribution at time  $t = 20$  minutes, with adaptive nulling at four auxiliary sensors in effect. The focal-spot diameter with adaptive nulling is equivalent to the focal-spot diameter before adaptive nulling. Hot spots on the left and right sides of the target are eliminated. A comparison of the temperature distribution before and after nulling along the major axis ( $z = 0$ ) of the target ellipse is made in Figure 27. Similarly, the temperature distribution before and after nulling along the minor axis of the target ellipse is shown in Figure 28.

### 3.2.2 Convergence Check: 0.9525-cm Thermal Node Spacing

The convergence of the previous thermal simulations was verified by increasing the density of E-field observation probe positions by a factor of two, with a new spacing between points of 0.9525 cm, still with a 41 by 41 grid. The ring array operates as before at 120 MHz, and there are four auxiliary sensors laid out as shown in Figure 13. As the auxiliary positions are the same, the adaptive weights and covariance matrix eigenvalues in Figures 21 and 22, respectively, remain the same. From the parameter values in Table 1, all resistors in the finer-grid muscle-tissue phantom had a value of  $193.0^{\circ}\text{C/W}$  and all resistors in the water bolus had a value of  $174.4^{\circ}\text{C/W}$ . The value of the capacitors in the phantom muscle-tissue is  $2.95 \text{ J/}^{\circ}\text{C}$ . Again, a constant temperature of  $10^{\circ}\text{C}$  is enforced at each water-bolus node. The E-field scaling factors to raise the focal-point temperature to  $46^{\circ}\text{C}$  before and after nulling are 76.5 dB and 78.4 dB, respectively. The finer-grid two-dimensional thermal distributions before and after nulling are shown in Figures 29 and 30, respectively. Although the temperature contours are smoother, the general agreement between these patterns and the coarser-grid patterns in Figures 23 and 26 are evident. Similarly, one-dimensional thermal pattern cuts with the finer grid are shown in Figures 31 ( $x$  axis) and 32 ( $z$  axis); good agreement with the coarse-grid patterns (Figures 27 and 28) is observed. In particular, the finer detail in Figure 31 shows that the hot spots are at a  $42^{\circ}\text{C}$  level compared to the  $41^{\circ}\text{C}$  level

observed for the coarse grid (Figure 24). Thus, convergence of the coarse-grid thermal patterns is demonstrated.

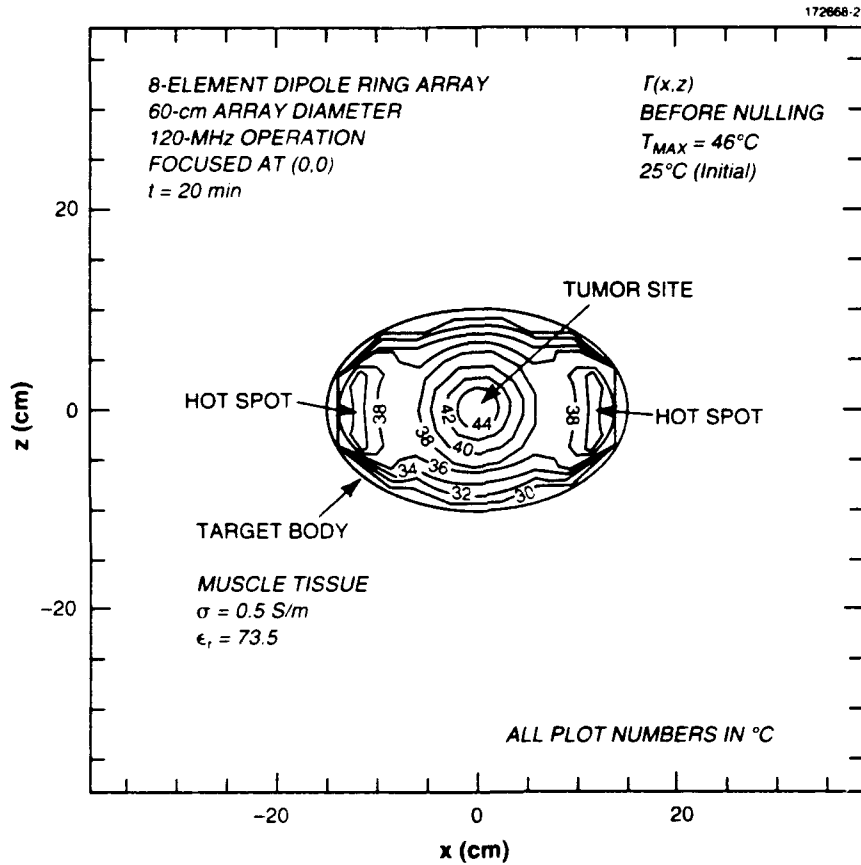


Figure 23. Simulated two-dimensional thermal pattern at time  $t = 20$  minutes before nulling in elliptical phantom muscle-tissue target surrounded with  $10^\circ\text{C}$  constant-temperature water bolus. The incident RF power distribution, from Figure 14, is at 120 MHz. Temperature contour levels are given in  $2^\circ\text{C}$  steps. Hot spots on the left and right sides of the target are observed.

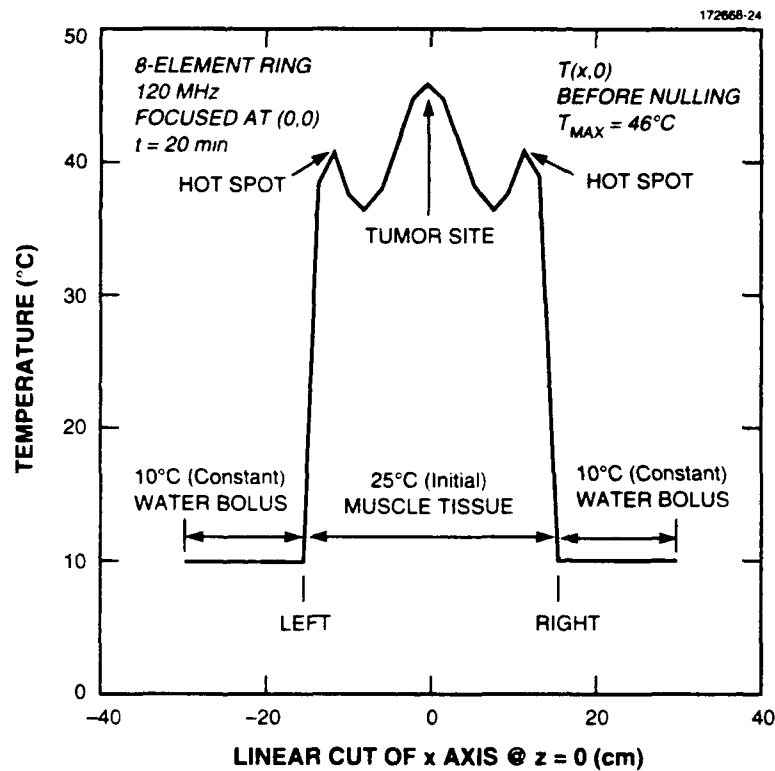


Figure 24. Simulated one-dimensional ( $z = 0$ ) thermal pattern at time  $t = 20$  minutes before nulling in elliptical phantom muscle-tissue target surrounded with  $10^\circ\text{C}$  constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. Hot spots on the left and right sides of the target are observed.



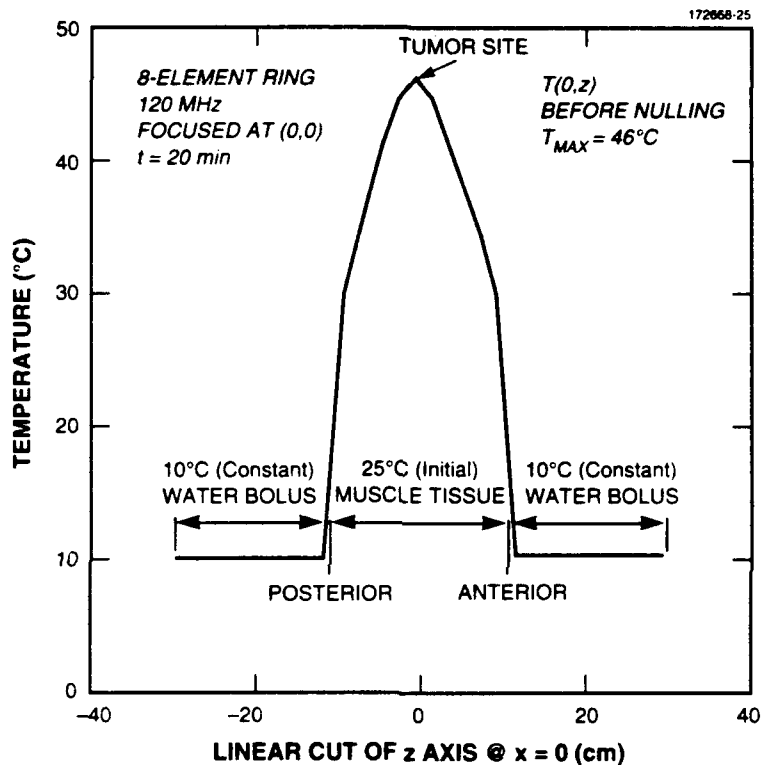


Figure 25. Simulated one-dimensional ( $x = 0$ ) thermal pattern at time  $t = 20$  minutes before nulling in elliptical phantom muscle-tissue target surrounded with  $10^\circ\text{C}$  constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. No undesired hot spots are present.

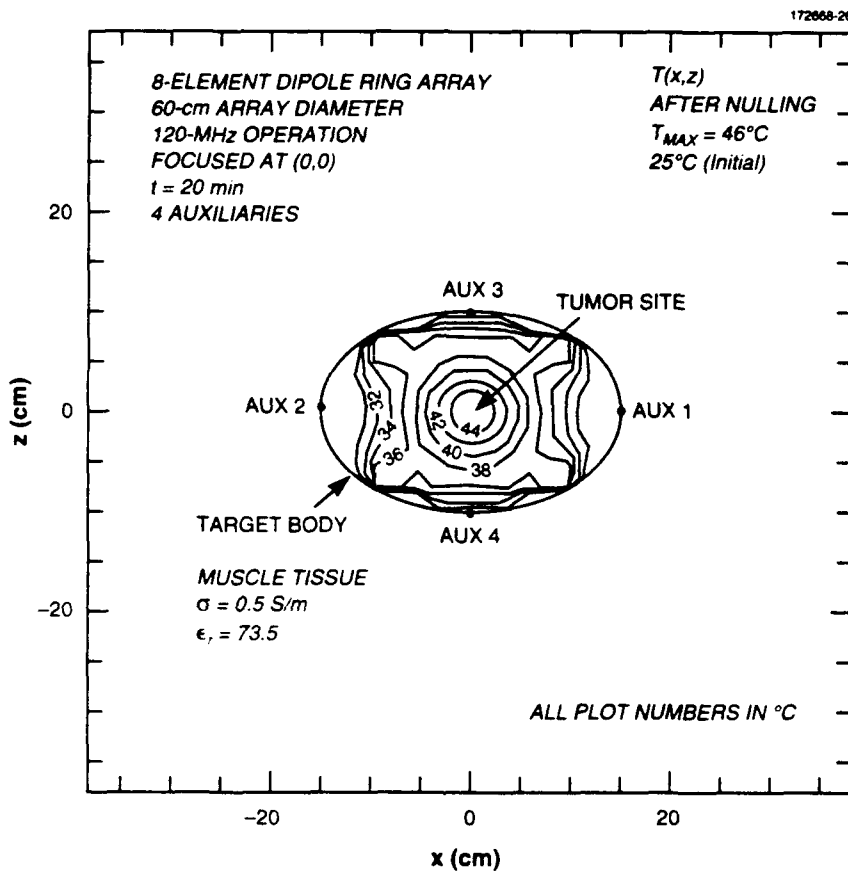


Figure 26. Simulated two-dimensional thermal pattern at time  $t = 20$  minutes (with adaptive nulling at four auxiliary sensors in effect) in elliptical phantom muscle-tissue target surrounded with  $10^\circ\text{C}$  constant-temperature water bolus. The adapted incident RF power distribution, from Figure 18, is at 120 MHz. Temperature contour levels are given in  $2^\circ\text{C}$  steps. Hot spots on the left and right sides of the target are eliminated.

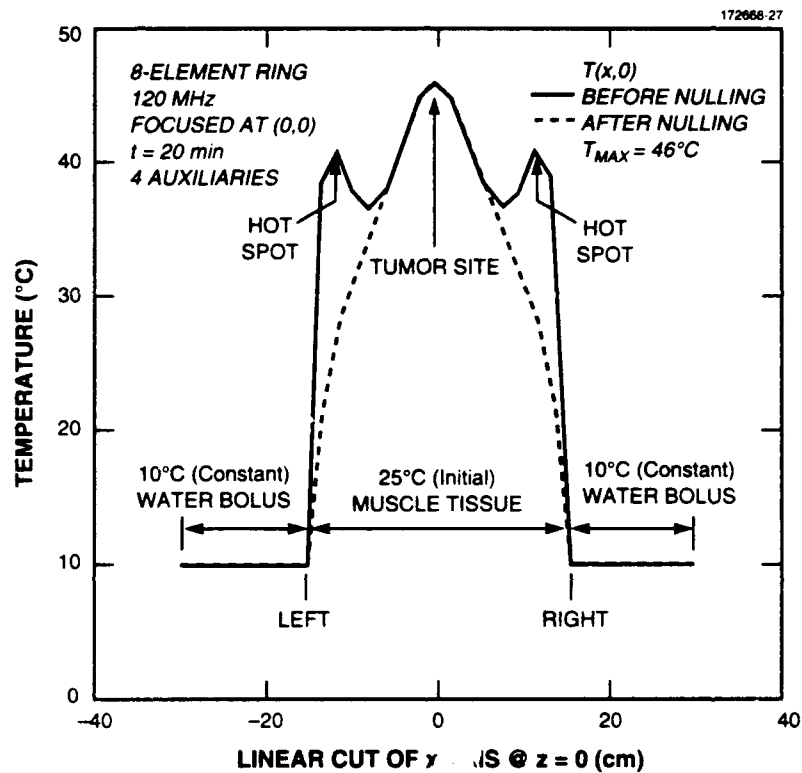


Figure 27. Simulated one-dimensional ( $z = 0$ ) thermal patterns at time  $t = 20$  minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with 10 $^{\circ}\text{C}$  constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. Hot spots on the left and right sides of the target are clearly eliminated by the adaptive nulling process. Four auxiliary sensors are used in the adaptive process.

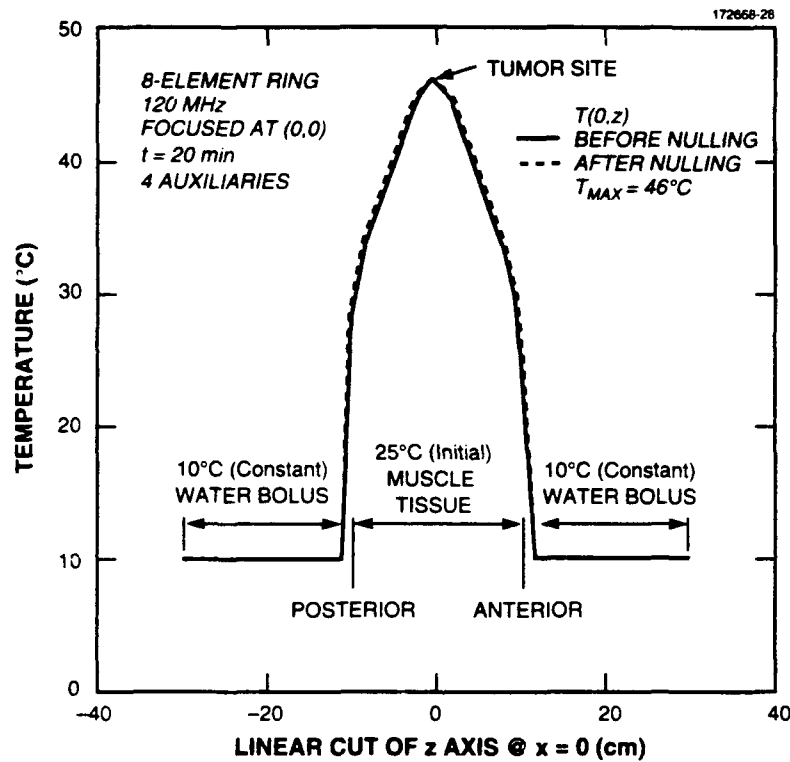


Figure 28. Simulated one-dimensional ( $x = 0$ ) thermal patterns at time  $t = 20$  minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with 10 $^{\circ}$ C constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. No undesired hot spots are present. Four auxiliary sensors are used in the adaptive process.

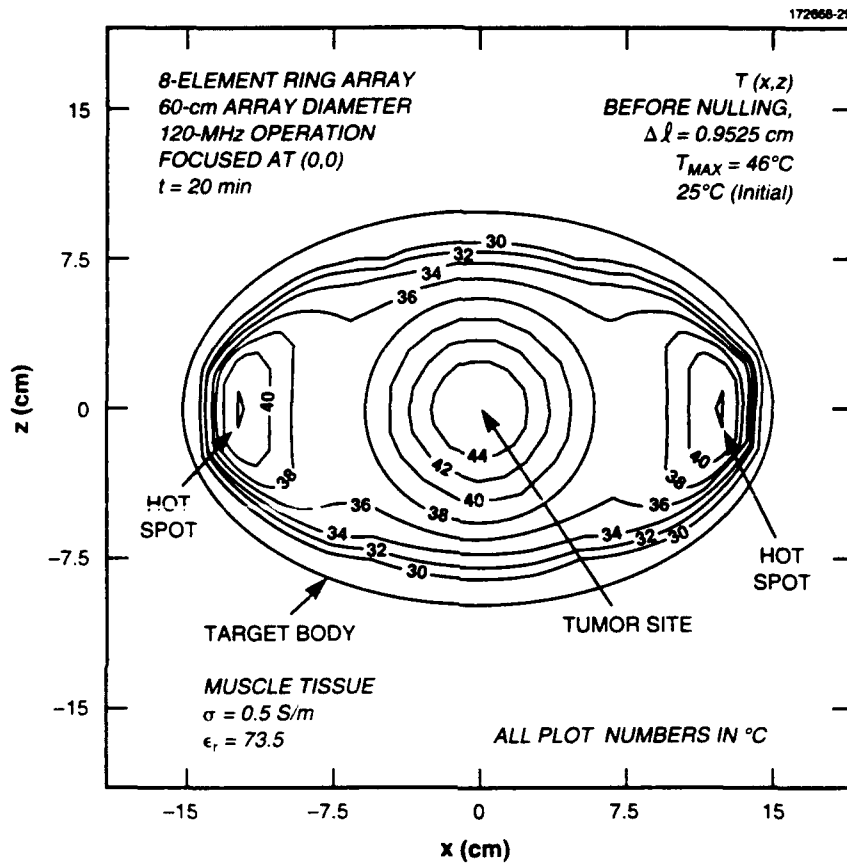


Figure 29. *E*-field probe-sample-spacing convergence check for simulated two-dimensional thermal pattern at time  $t = 20$  minutes (before adaptive nulling) in elliptical phantom muscle-tissue target surrounded with  $10^\circ\text{C}$  constant-temperature water bolus. The quiescent incident RF power distribution is at 120 MHz. Temperature contour levels are given in  $^\circ\text{C}$  steps. The grid spacing is one-half the spacing of that in Figure 23. Hot spots on the left and right sides of the target are present, as previously observed for the coarser probe-sample spacing.

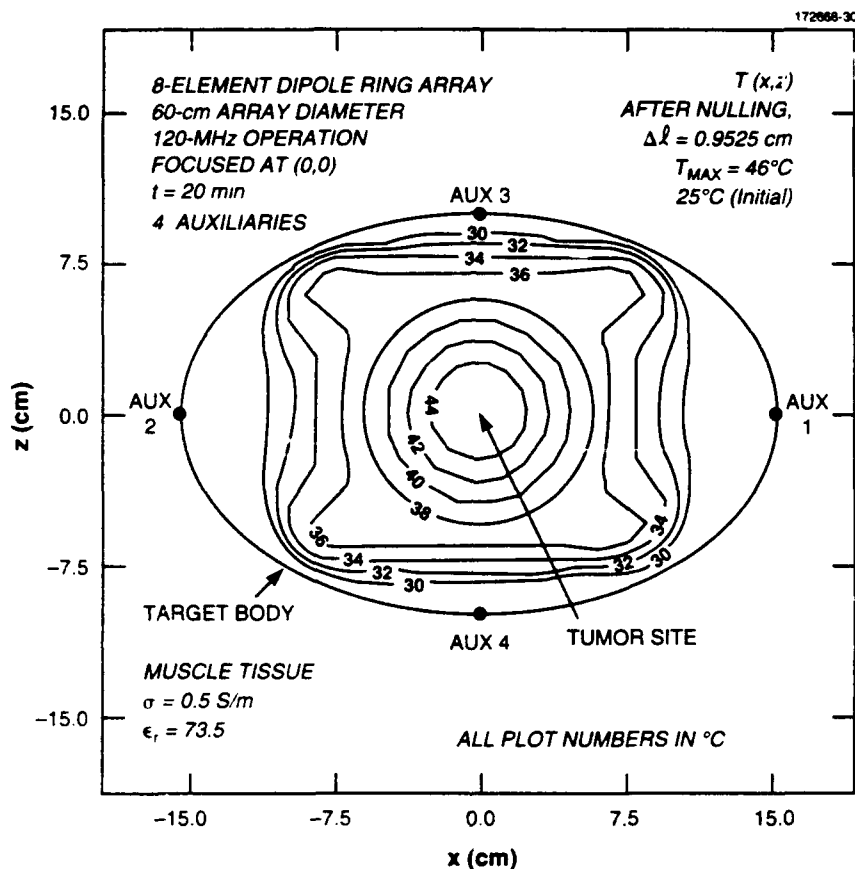


Figure 30. E-field probe-sample-spacing convergence check for simulated two-dimensional thermal pattern at time  $t = 20$  minutes (with adaptive nulling in effect) in elliptical phantom muscle-tissue target surrounded with  $10^\circ\text{C}$  constant-temperature water bolus. The adapted incident RF power distribution is at 120 MHz. Temperature contour levels are given in  $2^\circ\text{C}$  steps. The grid spacing is one-half the spacing of that in Figure 26. Hot spots on the left and right sides of the target are eliminated, as previously observed for the coarser probe-sample spacing.

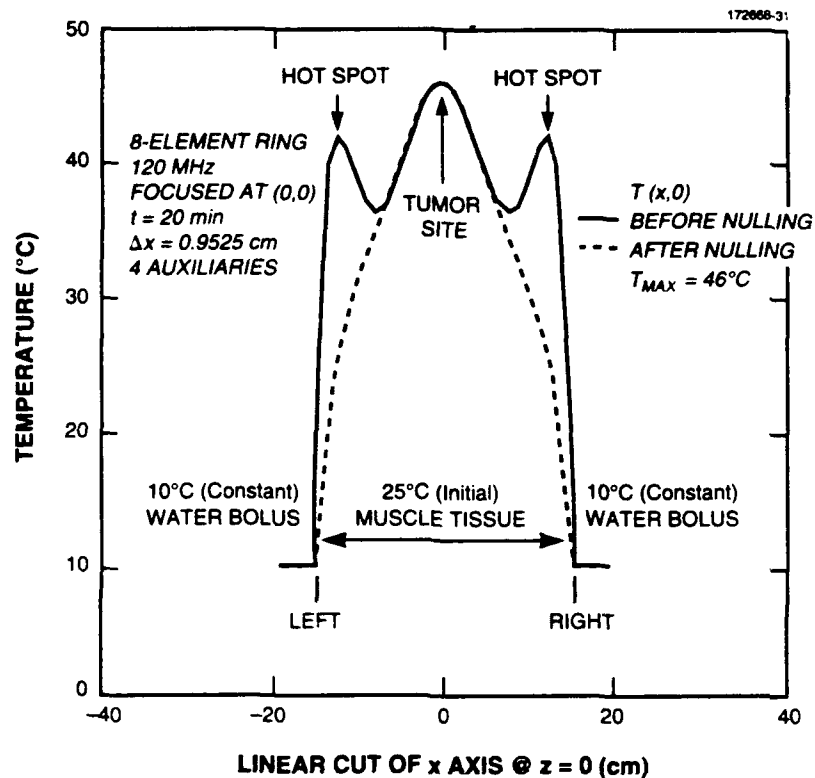


Figure 31. E-field probe-sample-spacing convergence check for simulated one-dimensional ( $z = 0$ ) thermal patterns at time  $t = 20$  minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with  $10^{\circ}\text{C}$  constant-temperature water bolus. The quiescent incident RF power distribution is at 120 MHz with 0.9525-cm sample spacing. Hot spots on the left and right sides of the target are eliminated by the adaptive nulling process, as previously observed in Figure 27. Four auxiliary sensors are used in the adaptive process.

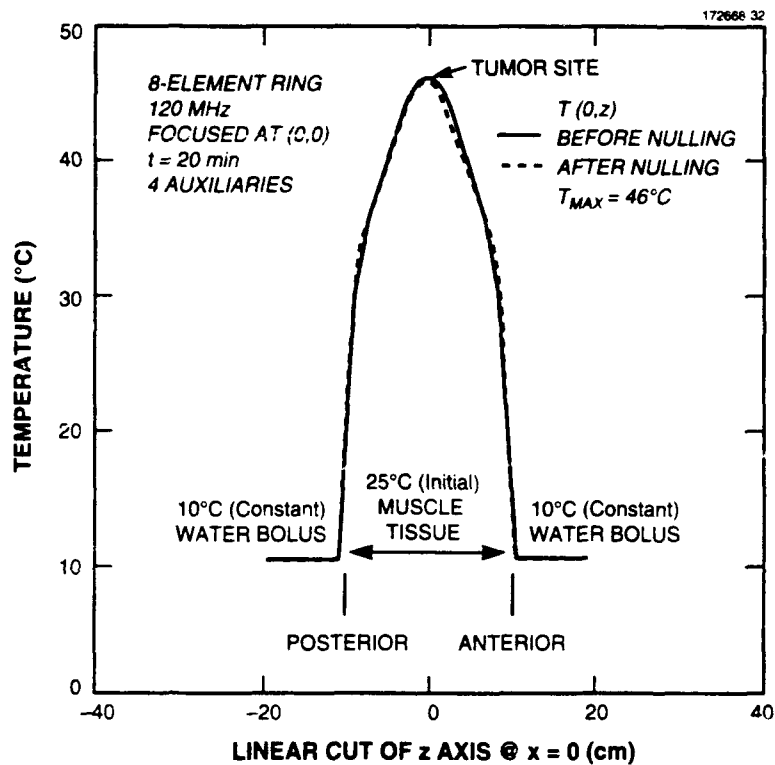


Figure 32. *E*-field probe-sample-spacing convergence check for simulated one-dimensional ( $x = 0$ ) thermal patterns at time  $t = 20$  minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with  $10^{\circ}\text{C}$  constant-temperature water bolus. The quiescent incident RF power distribution is at 120 MHz with 0.9525-cm sample spacing. No undesired hot spots are present. Four auxiliary sensors are used in the adaptive process.



#### 4. CONCLUSION

Focused near-field adaptive nulling has been applied to the problem of generating therapeutic temperature distributions, free of undesired hot spots, for deep-regional cancer treatment in a target body. A noninvasive adaptive hyperthermia system concept has been described and is analyzed in detail. Auxiliary short-dipole nulling sensors are positioned on the surface of the target. Due to the finite width of an electric-field null, a null formed at the target surface extends into the interior region of the target. When the width of the null is properly chosen, undesired hot spots inside the target are eliminated while simultaneously focusing on a deep-seated tumor. The resolution between a deep null and focus is limited by the half-power beamwidth of the hyperthermia array. The resolution can be somewhat enhanced by using weak nulls whenever the spacing between the null and focus is less than one half-power beamwidth. The depth of null is controlled by the SNR at the auxiliary probe position.

A theory for analyzing adaptive nulling with a phased array in an infinite homogeneous conducting medium has been developed. The method of moments is used to compute the electric field at a short-dipole sensor due to a thin-wire dipole ring array. The SMI algorithm is used to adaptively control the transmit array weights and to form radiation pattern nulls. The method used for analyzing the transient thermal behavior of an RF-illuminated target by using an equivalent electric circuit network has been described.

Computer simulations of the electric field and induced temperature distribution for an eight-element dipole ring array at 120 MHz have been presented. Four auxiliary E-field short-dipole sensors are used in eliminating two widely separated hot spots surrounding the array focus at the center of an elliptical target with dimensions 30 cm by 20 cm. Calculated data indicate that simultaneous nulling and focusing can yield desirable electric-field distributions for hyperthermia. Undesired hot spots controlled with an insufficient number of auxiliary nulling probes have been shown to simply redistribute within the target. Thus, an adequate number of auxiliary probes must be provided to ensure that no undesired hot spots are formed in deep-regional hyperthermia therapy. Although the computer simulations are implemented for a phantom target, adaptive nulling may prove beneficial in clinical trials of hyperthermia with living targets. Further adaptive-nulling simulations with inhomogeneous targets are desirable, as are experimental measurements of adaptive hyperthermia in phantom targets. A study of proper number and positioning of the non-invasive sensors for treating arbitrary tumor positions needs to be performed. The adaptive-nulling technique described here should be applicable to both invasive and noninvasive RF hyperthermia systems, as well as ultrasound hyperthermia systems.

## APPENDIX A

### SYSTEM DEGRADATION DUE TO INSUFFICIENT NUMBER OF AUXILIARY PROBES

This section shows simulation results which indicate that an insufficient number of auxiliary nulling probes will degrade adaptive hyperthermia system performance. The simulation parameters are the same as presented in Section 3, except only two auxiliary probes ( $N_{aux} = 2$ ) are used to form nulls at the surface of the elliptical muscle-tissue target. The geometry used in the simulations is shown in Figure A-1. A 60-cm diameter ring array of eight dipoles uniformly surround a fictitious elliptical target zone with major axis 30 cm and minor axis 20 cm. The length of each perfectly conducting center-fed dipole array element, at 120 MHz in the infinite homogeneous muscle tissue, is  $\lambda/2$  or 13.25 cm. The array focus is assumed to be at the origin, and two auxiliary short-dipole sensors with length 1.27 cm are positioned at (15 cm, 0) and (-15 cm, 0). In rectangular coordinates, each dipole is oriented in the  $\hat{y}$  direction and the feed terminals of each dipole are located at  $y = 0$ . The quiescent radiation patterns and thermal distributions are the same as

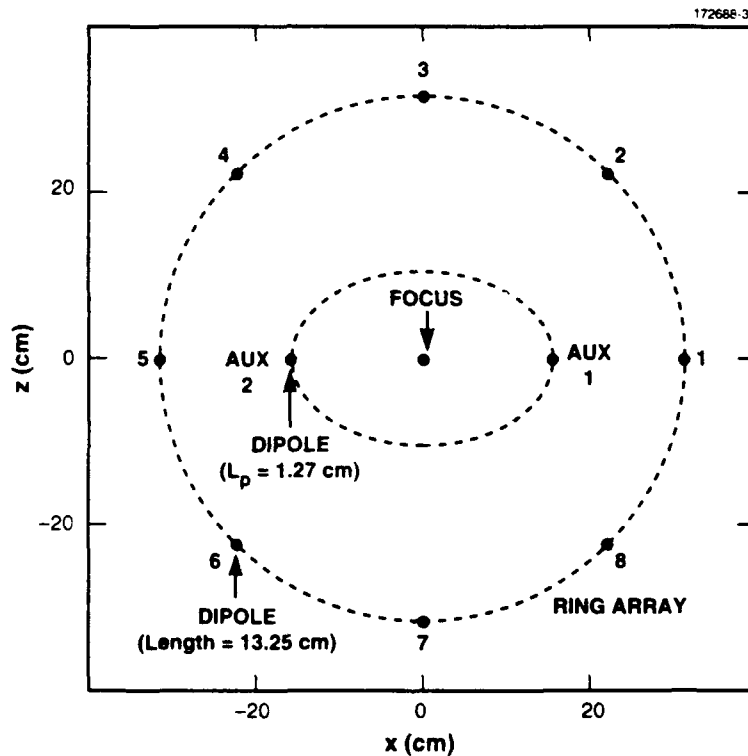


Figure A-1. Geometry for eight-element ring array and two E-field auxiliary sensors.

presented in Figures 14, 15, 16, 17, 23, 24, and 25.

With only two auxiliary sensors, the two-dimensional adapted electric-field radiation pattern shown in Figure A-2 indicates that both auxiliary positions are nulled. However, the two-dimensional adaptive thermal distribution in Figure A-3 shows that the quiescent hot spots (see Figure 23) have only been redistributed. The one-dimensional thermal distribution in Figure A-4 shows that the hot spots are reduced on the left and right sides of the elliptical target, and Figure A-5 shows that the hot spots are redistributed to lie along the  $z$  axis. Thus, two additional auxiliary probes (probes 3 and 4 in Figure 13) are necessary to avoid the possibility of redistributed hot spots. Finally, the adaptive weights and covariance matrix eigenvalues are shown in Figures A-6 and A-7, respectively. There are only small differences between the weights and eigenvalues compared to the four-auxiliary probe case (see Figures 21 and 22). The transmit weights cover a 7-dB dynamic range and there are only two nonzero eigenvalues. The probe-array power outputs before and after adaptive nulling are 31.4 dB and 0.0 dB, respectively. Thus, the interference cancellation is to the noise level, or -31.4 dB. An output file for the moment-method simulation for this section is given in Appendix B.

# E-FIELD AFTER NULLING; 2 AUXILIARIES

172668-34

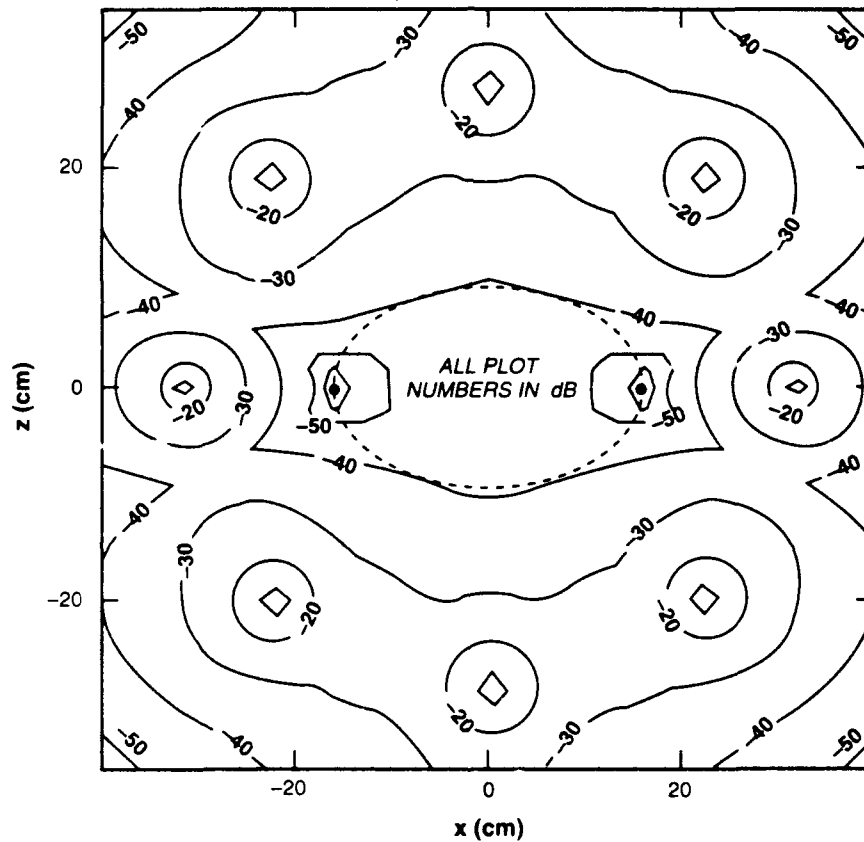


Figure A-2. Simulated two-dimensional adaptive radiation pattern at 120 MHz for eight-element ring array in infinite homogeneous conducting medium (phantom muscle tissue:  $\epsilon_r = 73.5$ ,  $\sigma = 0.5$ ). Radiation contour levels are given in 10-dB steps. Two auxiliary sensors are used in forming the adaptive pattern. The quiescent focus is at (0,0).

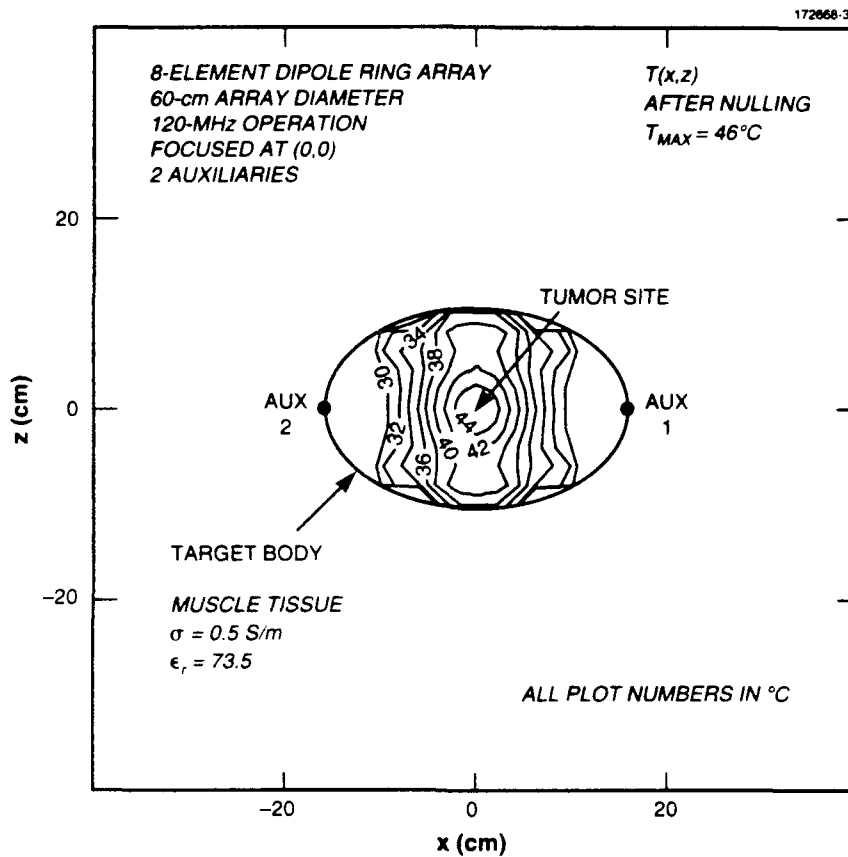


Figure A-3. Simulated two-dimensional thermal pattern at time  $t = 20$  minutes (with adaptive nulling at only two auxiliary sensors in effect) in elliptical phantom muscle-tissue target surrounded with  $10^{\circ}\text{C}$  constant-temperature water bolus. The adapted incident RF power distribution, from Figure 18, is at 120 MHz. Temperature contour levels are given in  $2^{\circ}\text{C}$  steps. Initial hot spots (before nulling) on the left and right sides of the target (see Figure 23) are redistributed to the top and bottom (anterior and posterior positions).

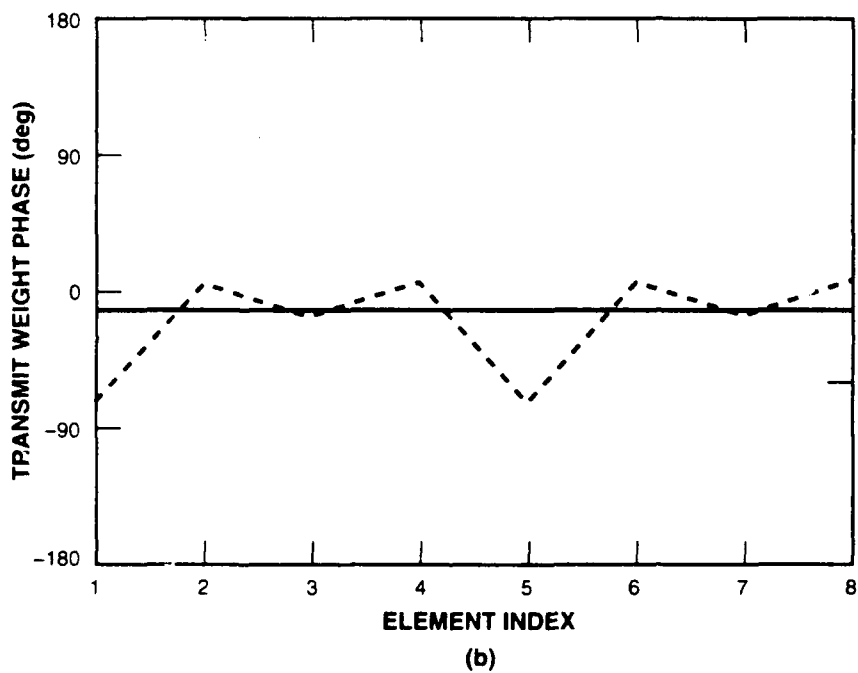
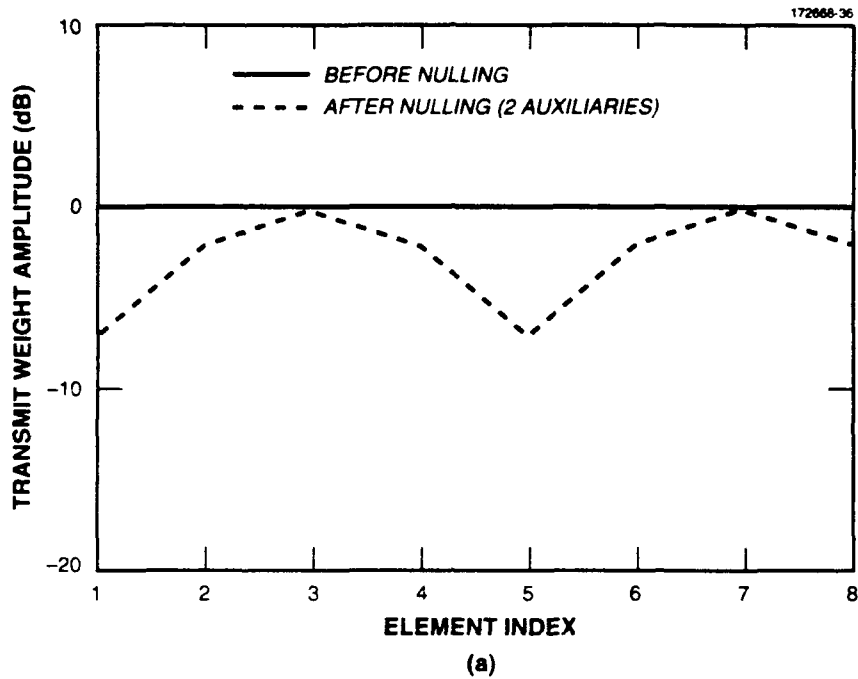


Figure A-4. Simulated one-dimensional ( $z = 0$ ) thermal patterns at time  $t = 20$  minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with  $10^\circ\text{C}$  constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. Hot spots on the left and right sides of the target are eliminated by the adaptive nulling process. Two auxiliary sensors are used in the adaptive process.

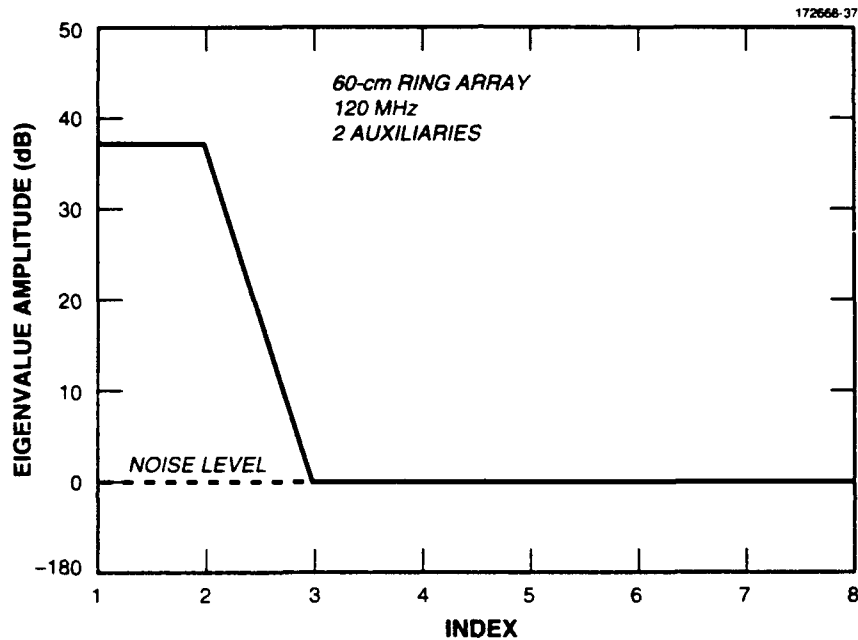


Figure A-5. Simulated one-dimensional ( $x = 0$ ) thermal patterns at time  $t = 20$  minutes before and after nulling in elliptical phantom muscle-tissue target surrounded with  $10^\circ\text{C}$  constant-temperature water bolus. The quiescent incident RF power distribution, from Figure 14, is at 120 MHz. Two undesired hot spots are present in the adaptive pattern. Two auxiliary sensors are used in the adaptive process.

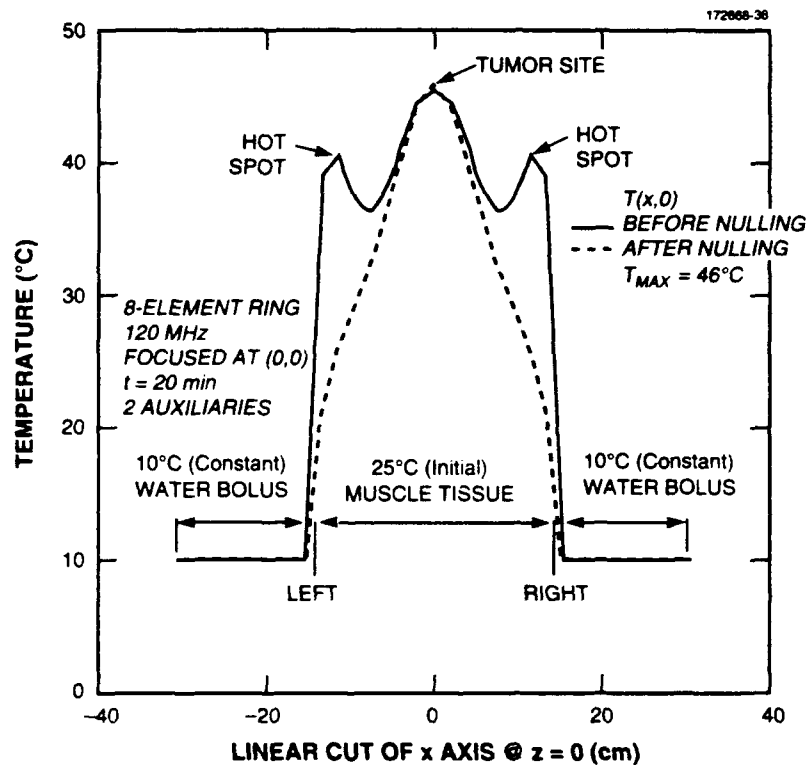


Figure A-6. Transmit array weights before and after adaptive nulling. A dynamic range of about 7 dB is evident for the adaptive weights. Two auxiliary sensors are used in the adaptive process. (a) Amplitude; (b) Phase.



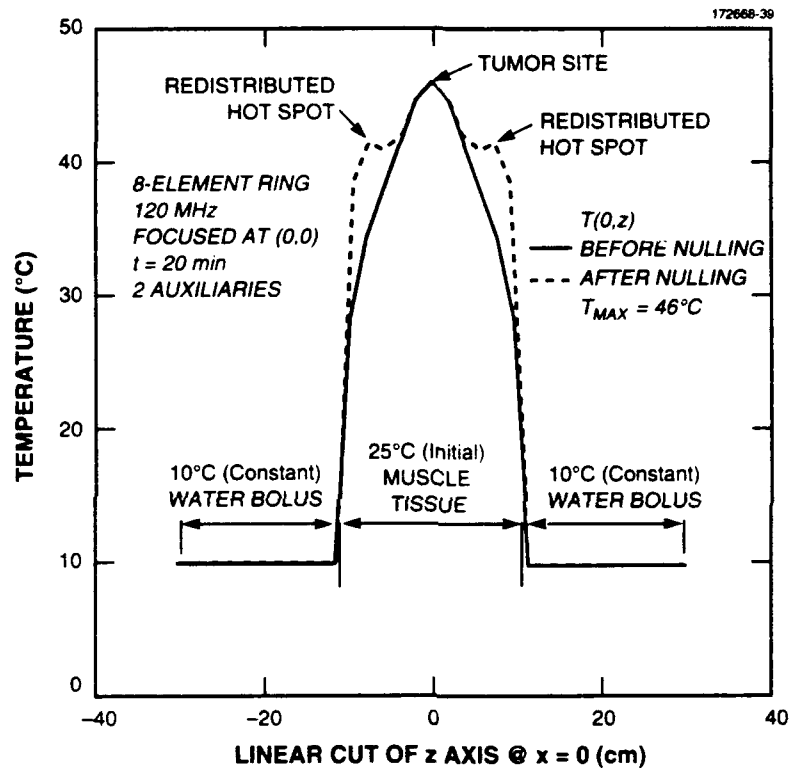


Figure A-7. Channel covariance matrix eigenvalues (degrees of freedom) used in the adaptive process with two auxiliary sensors.

## APPENDIX B

### SOFTWARE DOCUMENTATION

This appendix lists sample input and output files for the adaptive hyperthermia simulation. Listings of the key FORTRAN programs that implement adaptive nulling in a homogeneous conducting medium are also given. Additional moment-method software not listed here is contained in Richmond [37].

The first data file (four auxiliary sensors) is used to generate the E-field results presented in Section 3.1. The second data file (two auxiliary sensors) was used in calculating the electric-field distribution presented in Appendix A. The corresponding output files give the values for the array mutual coupling, quiescent and adaptive transmit weights, covariance matrix, eigenvalues, and cancellation.

```

***Input data file for adaptive nulling with four auxiliary probes.
***sdipjamhyper data file, filename sdipjamhyper.datacirconicrr4
&DIPOLE NCOLX=8,NROWY=1,HZIN=0.001,HLIN=2.6,
  DXIN=6.888,DYIN=6.888,ARADIN=0.0039,
  ICIRC=1,CRADIN=11.81,HLSIN=0.25,
  IWL=0,FCHZ=120.0E6,BWFHZ=1.0E0,NFREQ=5,IWA=0,
  NPDX=0,NXDUM=0,NYDUM=0,ER3=73.5,SIG3=0.5,TD3=-1.0,
  ZLOAD=50.0,ZCHAR=0.0,NGEN=8,IGEN=0,
  NSCANS=1,
  THSINC=5.0,
  IMUT=1,IBLTSL=0,
  IENORM=1,ICHEB=0,SLLDB=20.,EDGTDB=0.,
  IPATRN=1,IPRCOM=1,IANGLP=0,
  NPHCT=0,NTHPT=499,
  THDR=180.,THDMIN=-90.,
  NCOLXN=121,NROWYN=1,NCOLZN=1,
  RLSYIN=0.0,RLSZIN=0.0,
  NCOLXN=117,NROWYN=1,NCOLZN=1,
  INEAR=1,
  IPOL=2,IGRNDP=0,
  ITLTPR=0,ITLTDP=0,
  NFCOLX=1,NFROWY=1,
  IANTX=1,IAN TY=0,NPOWER=0,
  IPCONN=1,IPCONF=0,IPCUTF=0,IPCFX=0,IPCFY=0,IPCFZ=0,
  ITEK=0,
  IQUAN=0,IRNERR=0,ELERDB=0.02,ELERDG=0.2,NBMOD=12,
  NRAN=1,NBADWT=32,AWERDB=0.0,AWERDG=0.0,
  NAUX=7,IAUXA(1)=1,2,3,4,5,6,7,
  IATTEN=1,
  NJAMS=7,ISLC=0,AUXADB(1)=8*0.0,
  PWRJDB(1)=40.,40.,15.,15.,3*-99.0,
  YJAMIN(1)=7*0.0,
  XFOCIN=0.0,ZFOCIN=0.0,
  XJAMIN(1)=5.9,-5.9,2*0.0,3*-0.0,
  ZJAMIN(1)=0.0,0.0,4.0,-4.0,3*0.0
  YNIN=0.0,
  NCOLXN=101,NTHPT=101,
  XNIN=-15.,ZNIN=-15.,RLSXIN=30.,RLSZIN=30.,NCOLXN=41,NCOLZN=41,
&END

```

```

***Output data file for adaptive nulling with four auxiliary probes.
***sdiipjamhyper data file, filename sdiipjamhyper.datacirconicrr4
XJAMIN(1),YJAMIN(1),ZJAMIN(1)=      5.900      0.000      0.000
FGHZ=      0.1200000
DX,DY,HL,ARAD=      0.17496      0.17496      0.06604      0.00010
IV,VTA=  1      0.5916E-02  0.2211E-02
IV,VTA=  2      0.5916E-02  0.2211E-02
IV,VTA=  3      0.5916E-02  0.2211E-02
IV,VTA=  4      0.5916E-02  0.2211E-02
IV,VTA=  5      0.5916E-02  0.2211E-02
IV,VTA=  6      0.5916E-02  0.2211E-02
IV,VTA=  7      0.5916E-02  0.2211E-02
IV,VTA=  8      0.5916E-02  0.2211E-02
*****array mutual impedance matrix (first row)*****
Z(1,  1)=  0.91705E+02  0.12403E+02
Z(1,  2)=-0.33552E-01  0.19136E+00
Z(1,  3)=-0.14488E-01-0.54125E-02
Z(1,  4)=  0.29420E-02  0.13780E-02
Z(1,  5)=  0.15283E-02-0.11371E-02
Z(1,  6)=  0.29420E-02  0.13780E-02
Z(1,  7)=-0.14488E-01-0.54125E-02
Z(1,  8)=-0.33552E-01  0.19136E+00
NEL,NCOLX,NROWY=      8      8      1
CURRENTS
  1  1.000000      0.683E-04      13.
  2  1.000000      0.683E-04      13.
  3  1.000000      0.683E-04      13.
  4  1.000000      0.683E-04      13.
  5  1.000000      0.683E-04      13.
  6  1.000000      0.683E-04      13.
  7  1.000000      0.683E-04      13.
  8  1.000000      0.683E-04      13.
IC,RWTA=  1  0.35355E+00
IC,RWTA=  2  0.35355E+00
IC,RWTA=  3  0.35355E+00
IC,RWTA=  4  0.35355E+00
IC,RWTA=  5  0.35355E+00
IC,RWTA=  6  0.35355E+00
IC,RWTA=  7  0.35355E+00
IC,RWTA=  8  0.35355E+00
I,CWTA(I,1)=  1  0.34510E+00-0.76830E-01
I,CWTA(I,1)=  2  0.34510E+00-0.76830E-01
I,CWTA(I,1)=  3  0.34510E+00-0.76830E-01
I,CWTA(I,1)=  4  0.34510E+00-0.76830E-01
I,CWTA(I,1)=  5  0.34510E+00-0.76830E-01
I,CWTA(I,1)=  6  0.34510E+00-0.76830E-01
I,CWTA(I,1)=  7  0.34510E+00-0.76830E-01
I,CWTA(I,1)=  8  0.34510E+00-0.76830E-01
*****ring array weights before nulling (amp,phase)*****
I=  1  CWTADB,CWTADG=      0.00000      -12.55098
I=  2  CWTADB,CWTADG=      0.00000      -12.55099
I=  3  CWTADB,CWTADG=      0.00000      -12.55098
I=  4  CWTADB,CWTADG=      0.00000      -12.55097
I=  5  CWTADB,CWTADG=      0.00000      -12.55098
I=  6  CWTADB,CWTADG=      0.00000      -12.55097
I=  7  CWTADB,CWTADG=      0.00000      -12.55098
I=  8  CWTADB,CWTADG=      0.00000      -12.55097
Z(1,  1)=  0.91705E+02  0.12403E+02
Z(1,  2)=-0.33552E-01  0.19136E+00

```

Z(1, 3)=-0.14488E-01-0.54125E-02  
 Z(1, 4)= 0.29420E-02 0.13780E-02  
 Z(1, 5)= 0.15283E-02-0.11371E-02  
 Z(1, 6)= 0.29420E-02 0.13780E-02  
 Z(1, 7)=-0.14488E-01-0.54125E-02  
 Z(1, 8)=-0.33552E-01 0.19136E+00  
 NEL,NCOLX,NROWY= 8 8 1  
 II,PWRJ IN POWER= 1 0.10000E+05  
 II,PWRJ IN POWER= 2 0.10000E+05  
 II,PWRJ IN POWER= 3 0.31623E+02  
 II,PWRJ IN POWER= 4 0.31623E+02  
 II,PWRJ IN POWER= 5 0.12589E-09  
 II,PWRJ IN POWER= 6 0.12589E-09  
 II,PWRJ IN POWER= 7 0.12589E-09

\*\*\*\*\*covariance matrix\*\*\*\*\*

I,J,CNDB,PHASEN=	1	1	36.35	0.00
I,J,CNDB,PHASEN=	1	2	31.68	91.33
I,J,CNDB,PHASEN=	1	3	24.99	-117.95
I,J,CNDB,PHASEN=	1	4	20.88	6.26
I,J,CNDB,PHASEN=	1	5	20.72	-0.14
I,J,CNDB,PHASEN=	1	6	20.88	6.26
I,J,CNDB,PHASEN=	1	7	24.99	-117.95
I,J,CNDB,PHASEN=	1	8	31.68	91.33
I,J,CNDB,PHASEN=	2	1	31.68	-91.33
I,J,CNDB,PHASEN=	2	2	27.05	0.00
I,J,CNDB,PHASEN=	2	3	20.23	155.55
I,J,CNDB,PHASEN=	2	4	8.12	177.91
I,J,CNDB,PHASEN=	2	5	20.90	-6.14
I,J,CNDB,PHASEN=	2	6	8.28	177.98
I,J,CNDB,PHASEN=	2	7	20.24	155.46
I,J,CNDB,PHASEN=	2	8	27.04	0.00
I,J,CNDB,PHASEN=	3	1	24.99	117.95
I,J,CNDB,PHASEN=	3	2	20.23	-155.55
I,J,CNDB,PHASEN=	3	3	16.67	0.00
I,J,CNDB,PHASEN=	3	4	20.26	-155.43
I,J,CNDB,PHASEN=	3	5	25.01	117.95
I,J,CNDB,PHASEN=	3	6	20.27	-155.41
I,J,CNDB,PHASEN=	3	7	16.52	0.00
I,J,CNDB,PHASEN=	3	8	20.24	-155.46
I,J,CNDB,PHASEN=	4	1	20.88	-6.26
I,J,CNDB,PHASEN=	4	2	8.12	-177.91
I,J,CNDB,PHASEN=	4	3	20.26	155.49
I,J,CNDB,PHASEN=	4	4	27.08	0.00
I,J,CNDB,PHASEN=	4	5	31.71	-91.33
I,J,CNDB,PHASEN=	4	6	27.07	0.00
I,J,CNDB,PHASEN=	4	7	20.27	155.41
I,J,CNDB,PHASEN=	4	8	8.28	-177.98
I,J,CNDB,PHASEN=	5	1	20.72	0.14
I,J,CNDB,PHASEN=	5	2	20.90	6.14
I,J,CNDB,PHASEN=	5	3	25.01	-117.95
I,J,CNDB,PHASEN=	5	4	31.71	91.33
I,J,CNDB,PHASEN=	5	5	36.38	0.00
I,J,CNDB,PHASEN=	5	6	31.71	91.33
I,J,CNDB,PHASEN=	5	7	25.01	-117.95
I,J,CNDB,PHASEN=	5	8	20.90	6.14
I,J,CNDB,PHASEN=	6	1	20.88	-6.26
I,J,CNDB,PHASEN=	6	2	8.28	-177.98
I,J,CNDB,PHASEN=	6	3	20.27	155.41
I,J,CNDB,PHASEN=	6	4	27.07	0.00

I,J,CNDB,PHASEN=	6	6	31.71	-91.33
I,J,CNDB,PHASEN=	6	6	27.08	0.00
I,J,CNDB,PHASEN=	6	7	20.26	155.49
I,J,CNDB,PHASEN=	6	8	8.12	-177.91
I,J,CNDB,PHASEN=	7	1	24.99	117.95
I,J,CNDB,PHASEN=	7	2	20.24	-155.46
I,J,CNDB,PHASEN=	7	3	16.52	0.00
I,J,CNDB,PHASEN=	7	4	20.27	-155.41
I,J,CNDB,PHASEN=	7	5	25.01	117.95
I,J,CNDB,PHASEN=	7	6	20.26	-155.49
I,J,CNDB,PHASEN=	7	7	16.67	0.00
I,J,CNDB,PHASEN=	7	8	20.23	-155.65
I,J,CNDB,PHASEN=	8	1	31.68	-91.33
I,J,CNDB,PHASEN=	8	2	27.04	0.00
I,J,CNDB,PHASEN=	8	3	20.24	155.46
I,J,CNDB,PHASEN=	8	4	8.28	177.98
I,J,CNDB,PHASEN=	8	5	20.90	-6.14
I,J,CNDB,PHASEN=	8	6	8.12	177.91
I,J,CNDB,PHASEN=	8	7	20.23	155.55
I,J,CNDB,PHASEN=	8	8	27.05	0.00

\*\*\*\*\*eigenvalues\*\*\*\*\*

I,EVLDBN=	1	37.437
I,EVLDBN=	2	37.195
I,EVLDBN=	3	2.771
I,EVLDBN=	4	3.103
I,EVLDBN=	5	0.000
I,EVLDBN=	6	0.000
I,EVLDBN=	7	0.000
I,EVLDBN=	8	0.000

CPROD1,CPROD2= 0.13839E+04-0.85265E-13 0.10000E+01 0.00000E+00

INR NORMALIZATION PARAMETER, INRNOR= 1

I= 1	WANDB=	-12.318
I= 2	WANDB=	-8.734
I= 3	WANDB=	-7.602
I= 4	WANDB=	-8.734
I= 5	WANDB=	-12.318
I= 6	WANDB=	-8.734
I= 7	WANDB=	-7.602
I= 8	WANDB=	-8.734

I,WAN(I,1)=	1	0.11307E+00-0.21414E+00
I,WAN(I,1)=	2	0.34937E+00 0.10851E+00
I,WAN(I,1)=	3	0.32832E+00-0.25671E+00
I,WAN(I,1)=	4	0.34937E+00 0.10851E+00
I,WAN(I,1)=	5	0.11307E+00-0.21414E+00
I,WAN(I,1)=	6	0.34937E+00 0.10851E+00
I,WAN(I,1)=	7	0.32832E+00-0.25671E+00
I,WAN(I,1)=	8	0.34937E+00 0.10851E+00

\*\*\*\*\*adaptive array weights (amp.,phase)\*\*\*\*\*

I= 1	WANDB,WANDG=	-4.71576	-62.16515
I= 2	WANDB,WANDG=	-1.13211	17.25469
I= 3	WANDB,WANDG=	0.00000	-38.02192
I= 4	WANDB,WANDG=	-1.13210	17.25474
I= 5	WANDB,WANDG=	-4.71576	-62.16529
I= 6	WANDB,WANDG=	-1.13210	17.25474
I= 7	WANDB,WANDG=	0.00000	-38.02193
I= 8	WANDB,WANDG=	-1.13210	17.25469

\*\*\*\*\*cancellation\*\*\*\*\*

CPROD1,CPROD2= 0.12271E+01 0.12185E-13 0.10000E+01 0.00000E+00

INR NORMALIZATION PARAMETER, INRNOR= 1

```

INR= QUI,ADAP ,CANCEL=      31.411      0.889  -30.522  DB
CANCDB,NRAN,AVECAN=  -30.52207      1  -30.52207
***Input data file for adaptive nulling with two auxiliary probes.
***sdipjamhyper data file, filename sdipjamhyper.datacirconicrr3
&DIPOLE NCOLX=8,NROWY=1,HZIN=0.001,HLIN=2.6,
DIIN=6.888,DYIN=6.888,ARADIN=0.0039,
ICIRC=1,CRADIN=11.81,HLSIN=0.25,
IWL=0,FCHZ=120.0E6,BWFHZ=1.0E0,NFREQ=5,IWR=0,
NPDIX=0,NXDUM=0,NYDUM=0,ER3=73.5,SIG3=0.5,TD3=-1.0,
ZLOAD=50.0,ZCHAR=0.0,NGEN=8,IGEN=0,
NSCANS=1,
THSINC=5.0,
IMUT=1,IBLTS=0,
IENORM=1,ICHEB=0,SLDDB=20.,EDGTDB=0.,
IPATRN=1,IPRCOM=1,IANGLP=0,
NPHCT=0,NTHPT=499,
THDR=180.,THDMIN=-90.,
RLSYIN=0.0,RLSZIN=0.0,
NCOLXN=117,NROWYN=1,NCOLZN=1,
INEAR=1,
IPOL=2,IGRNDP=0,
ITLTPR=0,ITLTDP=0,
NFCOLX=1,NFROWY=1,
IANTX=1,IANTY=0,NPOWER=0,
IPCONN=1,IPCONF=0,IPCUTF=0,IPCFX=0,IPCFY=0,IPCFZ=0,
ITEK=0,
IQUAN=0,IRNERR=0,ELERDB=0.02,ELERDG=0.2,NBMOD=12,
NRAN=1,NBADWT=32,AWERDB=0.0,AWERDG=0.0,
NAUX=7,IAUXA(1)=1,2,3,4,5,6,7,
IATTEN=1,
INRNOR=1,
NJAMS=7,ISLC=0,AUXADB(1)=8*0.0,
PWRJDB(1)=40.,40.,5*-99.0,
YJAMIN(1)=7*0.0,
XFOCIN=0.0,ZFOCIN=0.0,
XJAMIN(1)=5.9,-5.9,2*0.0,2*-4.0,1*0.0,
ZJAMIN(1)=0.0,0.0,4.0,-4.0,3.0,-3.0,1*0.0
YNIN=0.0,
NCOLXN=101,NTHPT=101,
XNIN=-15.,ZNIN=-15.,RLSXIN=30.,RLSZIN=30.,NCOLXN=41,NCOLZN=41,
&END
***Output data file for adaptive nulling with two auxiliary probes.
***sdipjamhyper data file, filename sdipjamhyper.datacirconicrr3
XJAMIN(1),YJAMIN(1),ZJAMIN(1)=      5.900      0.000      0.000

FGHZ=      0.1200000
DX,DY,HL,ARAD=      0.17496      0.17496      0.06604      0.00010
IV,VTA=  1  0.5916E-02  0.2211E-02
IV,VTA=  2  0.5916E-02  0.2211E-02
IV,VTA=  3  0.5916E-02  0.2211E-02
IV,VTA=  4  0.5916E-02  0.2211E-02
IV,VTA=  5  0.5916E-02  0.2211E-02
IV,VTA=  6  0.5916E-02  0.2211E-02
IV,VTA=  7  0.5916E-02  0.2211E-02
IV,VTA=  8  0.5916E-02  0.2211E-02
*****array mutual impedance matrix (first row)*****
Z(1,  1)= 0.91705E+02 0.12403E+02
Z(1,  2)=-0.33552E-01 0.19136E+00
Z(1,  3)=-0.14488E-01-0.54125E-02

```

```

Z(1, 4)= 0.29420E-02 0.13780E-02
Z(1, 5)= 0.15283E-02-0.11371E-02
Z(1, 6)= 0.29420E-02 0.13780E-02
Z(1, 7)=-0.14488E-01-0.54125E-02
Z(1, 8)=-0.33552E-01 0.19136E+00
NEL,NCOLX,NROWY= 8 8 1
CURRENTS
  1 1.000000 0.683E-04 13.
  2 1.000000 0.683E-04 13.
  3 1.000000 0.683E-04 13.
  4 1.000000 0.683E-04 13.
  5 1.000000 0.683E-04 13.
  6 1.000000 0.683E-04 13.
  7 1.000000 0.683E-04 13.
  8 1.000000 0.683E-04 13.
IC,RWTA= 1 0.35355E+00
IC,RWTA= 2 0.35355E+00
IC,RWTA= 3 0.35355E+00
IC,RWTA= 4 0.35355E+00
IC,RWTA= 5 0.35355E+00
IC,RWTA= 6 0.35355E+00
IC,RWTA= 7 0.35355E+00
IC,RWTA= 8 0.35355E+00
I,CWTA(I,1)= 1 0.34510E+00-0.76830E-01
I,CWTA(I,1)= 2 0.34510E+00-0.76830E-01
I,CWTA(I,1)= 3 0.34510E+00-0.76830E-01
I,CWTA(I,1)= 4 0.34510E+00-0.76830E-01
I,CWTA(I,1)= 5 0.34510E+00-0.76830E-01
I,CWTA(I,1)= 6 0.34510E+00-0.76830E-01
I,CWTA(I,1)= 7 0.34510E+00-0.76830E-01
I,CWTA(I,1)= 8 0.34510E+00-0.76830E-01
*****ring array weights before nulling (amp,phase)*****
I= 1 CWTADB,CWTADG= 0.00000 -12.55098
I= 2 CWTADB,CWTADG= 0.00000 -12.55099
I= 3 CWTADB,CWTADG= 0.00000 -12.55098
I= 4 CWTADB,CWTADG= 0.00000 -12.55097
I= 5 CWTADB,CWTADG= 0.00000 -12.55098
I= 6 CWTADB,CWTADG= 0.00000 -12.55097
I= 7 CWTADB,CWTADG= 0.00000 -12.55098
I= 8 CWTADB,CWTADG= 0.00000 -12.55097
Z(1, 1)= 0.91705E+02 0.12403E+02
Z(1, 2)=-0.33552E-01 0.19136E+00
Z(1, 3)=-0.14488E-01-0.54125E-02
Z(1, 4)= 0.29420E-02 0.13780E-02
Z(1, 5)= 0.15283E-02-0.11371E-02
Z(1, 6)= 0.29420E-02 0.13780E-02
Z(1, 7)=-0.14488E-01-0.54125E-02
Z(1, 8)=-0.33552E-01 0.19136E+00
NEL,NCOLX,NROWY= 8 8 1
II,PWRJ IN POWER= 1 0.10000E+05
II,PWRJ IN POWER= 2 0.10000E+05
II,PWRJ IN POWER= 3 0.12589E-09
II,PWRJ IN POWER= 4 0.12589E-09
II,PWRJ IN POWER= 5 0.12589E-09
II,PWRJ IN POWER= 6 0.12589E-09
II,PWRJ IN POWER= 7 0.12589E-09
*****covariance matrix*****
I,J,CNDB,PHASEN= 1 1 36.35 0.00
I,J,CNDB,PHASEN= 1 2 31.68 91.33

```

I, J, CNDB, PHASEN=	1	3	24.98	-117.94
I, J, CNDB, PHASEN=	1	4	20.88	6.28
I, J, CNDB, PHASEN=	1	5	20.72	-0.14
I, J, CNDB, PHASEN=	1	6	20.88	6.28
I, J, CNDB, PHASEN=	1	7	24.98	-117.94
I, J, CNDB, PHASEN=	1	8	31.68	91.33
I, J, CNDB, PHASEN=	2	1	31.68	-91.33
I, J, CNDB, PHASEN=	2	2	27.05	0.00
I, J, CNDB, PHASEN=	2	3	20.24	155.47
I, J, CNDB, PHASEN=	2	4	8.24	177.97
I, J, CNDB, PHASEN=	2	5	20.90	-6.17
I, J, CNDB, PHASEN=	2	6	8.24	177.97
I, J, CNDB, PHASEN=	2	7	20.24	155.47
I, J, CNDB, PHASEN=	2	8	27.04	0.00
I, J, CNDB, PHASEN=	3	1	24.98	117.94
I, J, CNDB, PHASEN=	3	2	20.24	-155.47
I, J, CNDB, PHASEN=	3	3	16.62	0.00
I, J, CNDB, PHASEN=	3	4	20.27	-155.41
I, J, CNDB, PHASEN=	3	5	25.01	117.93
I, J, CNDB, PHASEN=	3	6	20.27	-155.41
I, J, CNDB, PHASEN=	3	7	16.52	0.00
I, J, CNDB, PHASEN=	3	8	20.24	-155.47
I, J, CNDB, PHASEN=	4	1	20.88	-6.28
I, J, CNDB, PHASEN=	4	2	8.24	-177.97
I, J, CNDB, PHASEN=	4	3	20.27	155.41
I, J, CNDB, PHASEN=	4	4	27.08	0.00
I, J, CNDB, PHASEN=	4	5	31.71	-91.33
I, J, CNDB, PHASEN=	4	6	27.07	0.00
I, J, CNDB, PHASEN=	4	7	20.27	155.41
I, J, CNDB, PHASEN=	4	8	8.24	-177.97
I, J, CNDB, PHASEN=	5	1	20.72	0.14
I, J, CNDB, PHASEN=	5	2	20.90	6.17
I, J, CNDB, PHASEN=	5	3	25.01	-117.93
I, J, CNDB, PHASEN=	5	4	31.71	91.33
I, J, CNDB, PHASEN=	5	5	36.38	0.00
I, J, CNDB, PHASEN=	5	6	31.71	91.33
I, J, CNDB, PHASEN=	5	7	25.01	-117.93
I, J, CNDB, PHASEN=	5	8	20.90	6.17
I, J, CNDB, PHASEN=	6	1	20.88	-6.28
I, J, CNDB, PHASEN=	6	2	8.24	-177.97
I, J, CNDB, PHASEN=	6	3	20.27	155.41
I, J, CNDB, PHASEN=	6	4	27.07	0.00
I, J, CNDB, PHASEN=	6	5	31.71	-91.33
I, J, CNDB, PHASEN=	6	6	27.08	0.00
I, J, CNDB, PHASEN=	6	7	20.27	155.41
I, J, CNDB, PHASEN=	6	8	8.24	-177.97
I, J, CNDB, PHASEN=	7	1	24.98	117.94
I, J, CNDB, PHASEN=	7	2	20.24	-155.47
I, J, CNDB, PHASEN=	7	3	16.52	0.00
I, J, CNDB, PHASEN=	7	4	20.27	-155.41
I, J, CNDB, PHASEN=	7	5	25.01	117.93
I, J, CNDB, PHASEN=	7	6	20.27	-155.41
I, J, CNDB, PHASEN=	7	7	16.62	0.00
I, J, CNDB, PHASEN=	7	8	20.24	-155.47
I, J, CNDB, PHASEN=	8	1	31.68	-91.33
I, J, CNDB, PHASEN=	8	2	27.04	0.00
I, J, CNDB, PHASEN=	8	3	20.24	155.47
I, J, CNDB, PHASEN=	8	4	8.24	177.97
I, J, CNDB, PHASEN=	8	5	20.90	-6.17



```

I,J,CNDB,PHASEN= 8 6 8.24 177.97
I,J,CNDB,PHASEN= 8 7 20.24 155.47
I,J,CNDB,PHASEN= 8 8 27.05 0.00
*****eigenvalues*****
I,EVLDBN= 1 37.195
I,EVLDBN= 2 37.437
I,EVLDBN= 3 0.000
I,EVLDBN= 4 0.000
I,EVLDBN= 5 0.000
I,EVLDBN= 6 0.000
I,EVLDBN= 7 0.000
I,EVLDBN= 8 0.000
CPROD1,CPROD2= 0.13835E+04-0.56843E-13 0.10000E+01 0.00000E+00
INR NORMALIZATION PARAMETER, INRNOR= 1
I= 1 WANDB= -14.003
I= 2 WANDB= -8.939
I= 3 WANDB= -6.886
I= 4 WANDB= -8.939
I= 5 WANDB= -14.003
I= 6 WANDB= -8.939
I= 7 WANDB= -6.886
I= 8 WANDB= -8.939
I,WAN(I,1)= 1 0.48427E-01-0.19349E+00
I,WAN(I,1)= 2 0.35635E+00 0.26440E-01
I,WAN(I,1)= 3 0.43481E+00-0.12564E+00
I,WAN(I,1)= 4 0.35635E+00 0.26441E-01
I,WAN(I,1)= 5 0.48427E-01-0.19349E+00
I,WAN(I,1)= 6 0.35635E+00 0.26441E-01
I,WAN(I,1)= 7 0.43481E+00-0.12564E+00
I,WAN(I,1)= 8 0.35635E+00 0.26441E-01
*****adaptive array weights (amp.,phase)*****
I= 1 WANDB,WANDG= -7.11720 -75.94859
I= 2 WANDB,WANDG= -2.05298 4.24348
I= 3 WANDB,WANDG= 0.00000 -16.11658
I= 4 WANDB,WANDG= -2.05297 4.24352
I= 5 WANDB,WANDG= -7.11719 -75.94872
I= 6 WANDB,WANDG= -2.05298 4.24352
I= 7 WANDB,WANDG= 0.00000 -16.11658
I= 8 WANDB,WANDG= -2.05297 4.24348
*****cancellation*****
CPROD1,CPROD2= 0.10001E+01-0.63768E-14 0.10000E+01 0.00000E+00
INR NORMALIZATION PARAMETER, INRNOR= 1
INR= QUI,ADAP ,CANCEL= 31.410 0.000 -31.410 DB
CANCDB,NRAN,AVECAN= -31.40966 1 -31.40966
*****makefile for moment method software*****
****file sdipjamhyperMake****
EXECUTABLE = sdipjamhyper.out
OBS = sdipjamhyper.o dzabgnloss.o \
      dpack2.o zabgnloss.o pack2.o fwgh.o \
      chebaf.o vvquan.o taylor.o \
      eigenv.o reordr.o ydipsubloss.o \
      plothyper.o kontek.o plabel.o \
      conturek.o circsubloss.o
# use tabs for continues
IL = /usr/lib/f68881/libm.il
FLAGS = -O1 -v -f68881
$(EXECUTABLE): $(OBS)
      dislink -lF77 $(FLAGS) -o $(EXECUTABLE) $(OBS) $(IL)

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sdipjamhyper.o: /home/ajf/hyperthermia/sdipjamhyper.f
f77 $(FLAGS) -c /home/ajf/hyperthermia/sdipjamhyper.f $(IL)

plothyper.o: /home/ajf/hyperthermia/plothyper.f
f77 $(FLAGS) -c /home/ajf/hyperthermia/plothyper.f $(IL)

dzabgnloss.o: /home/ajf/hyperthermia/dzabgnloss.f
f77 $(FLAGS) -c /home/ajf/hyperthermia/dzabgnloss.f $(IL)

dpack2.o: /home/ajf/monjam/dpack2.f
f77 $(FLAGS) -c /home/ajf/monjam/dpack2.f $(IL)

contek.o: /home/ajf/monjam/contek.f
f77 $(FLAGS) -c /home/ajf/monjam/contek.f $(IL)

plabel.o: /home/ajf/monjtr/plabel.f
f77 $(FLAGS) -c /home/ajf/monjtr/plabel.f $(IL)

conturek.o: /home/ajf/hyperthermia/conturek.f
f77 $(FLAGS) -c /home/ajf/hyperthermia/conturek.f $(IL)

zabgenloss.o: /home/ajf/hyperthermia/zabgenloss.f
f77 $(FLAGS) -c /home/ajf/hyperthermia/zabgenloss.f $(IL)

pack2.o: /home/ajf/monjam/pack2.f
f77 $(FLAGS) -c /home/ajf/monjam/pack2.f $(IL)

fwgh.o: /home/ajf/monjam/fwgh.f
f77 $(FLAGS) -c /home/ajf/monjam/fwgh.f $(IL)

chebaf.o: /home/ajf/monjam/chebaf.f
f77 $(FLAGS) -c /home/ajf/monjam/chebaf.f $(IL)

vwquan.o: /home/ajf/monjam/vwquan.f
f77 $(FLAGS) -c /home/ajf/monjam/vwquan.f $(IL)

taylor.o: /home/ajf/monjam/taylor.f
f77 $(FLAGS) -c /home/ajf/monjam/taylor.f $(IL)

eigen.o: /home/ajf/monjam/eigen.f
f77 $(FLAGS) -c /home/ajf/monjam/eigen.f $(IL)

reordr.o: /home/ajf/monjam/reordr.f
f77 $(FLAGS) -c /home/ajf/monjam/reordr.f $(IL)

ydipsubloss.o: /home/ajf/hyperthermia/ydipsubloss.f
f77 $(FLAGS) -c /home/ajf/hyperthermia/ydipsubloss.f $(IL)

cirsubloss.o: /home/ajf/hyperthermia/cirsubloss.f
f77 $(FLAGS) -c /home/ajf/hyperthermia/cirsubloss.f $(IL)

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*****file sdipjamhyper.f*****
C***PROGRAM SDIPJAMHYPER.F --- ANALYZES FINITE ARRAYS OF DIPOLES
C***IN LOSSY DIELECTRIC OR FREE SPACE.
C***THE DIPOLES ARE ASSUMED TO BE ORIENTED PARALLEL
C***TO THE PLANE OF THE GRID FOR A PLANAR ARRAY, OR THEY CAN BE
C***ARRANGED IN AN ANNULAR (RING) ARRAY CONFIGURATION.
C***RECEIVING CONDITIONS ARE ASSUMED.
C***DOUBLE-PRECISION VERSION
PARAMETER (NUMCHN=8)
PARAMETER (NUMAUX=8)

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PARAMETER (NUMJAM=7)
PARAMETER (NUMELM=8)
PARAMETER (NUMFRQ=5)
PARAMETER (NUMNPT=1681)
COMPLEX PS(1825),CZ(900),VA(NUMELM),Z(NUMELM,NUMELM)
COMPLEX VTA(NUMELM),VREFA,VRECVA(NUMELM)
COMPLEX VCV(NUMELM),VRECVX(NUMELM),CJ,CSUMA,VXA
CC***THE ABOVE MATRICES ARE DIMENSIONED BY THE NUMBER OF ELEMENTS
COMPLEX *16 COVNF(NUMCHN,NUMCHN),COVNF1(NUMCHN,NUMCHN)
COMPLEX *16 COVAJ(NUMCHN,NUMCHN),CINVCN(NUMCHN,NUMCHN)
COMPLEX *16 VCHA(NUMCHN,NUMFRQ)
COMPLEX *16 VMAJMA(NUMJAM,NUMFRQ)
COMPLEX *16 VAUXJA(NUMAUX,NUMJAM,NUMFRQ)
COMPLEX *8 VAXCWA(NUMAUX,NUMNPT)
C***NOTE DIMENS. VCHA(NCHAN,NFREQ),VMAJMA(NJAM,NFREQ) DIP00200
C VAUXJA(NAUX,NJAM,NFREQ),VAXCWA(NAUX,NPTS) DIP00210
COMPLEX *8 VXMNA(NUMNPT),ETASP,GAMSP
COMPLEX *16 EIGVAN(NUMCHN),EIGVEN(NUMCHN,NUMCHN)
COMPLEX *16 WANA(NUMCHN,1)
COMPLEX *16 WTCTR(1,NUMCHN),WQSLC(NUMCHN,1)
COMPLEX *16 WQNA(NUMELM,1),CMPROD(1,NUMCHN),WAN(NUMCHN,1)
COMPLEX *16 WANDMA(NUMELM,1)
COMPLEX *16 CWTA(NUMELM,1),ETADP,GAMDP
DIMENSION ACALPH(NUMELM),RWTAN(NUMELM),RWTB(NUMELM)
DIMENSION VXADB(NUMNPT),VXAPH(NUMNPT)
DIMENSION XC(NUMNPT),YC(NUMNPT),ZC(NUMNPT)
DIMENSION THSD(1),PHSD(1),THCT(1),PHCT(1) DIP00320
DIMENSION XJAMIN(NUMJAM),YJAMIN(NUMJAM),ZJAMIN(NUMJAM)
DIMENSION XJAM(NUMJAM),YJAM(NUMJAM),ZJAM(NUMJAM)
DIMENSION PWRJDB(NUMJAM) DIP00340
DIMENSION PCHADB(NUMNPT)
REAL *8 CNDB,PHASEN,DPDCR,WKE(144),EVLDBN DIP00370
REAL *8 PREALN,PIMAGN DIP00380
REAL *8 QINRDB,AINRDB,CANCDB,EXCPCB DIP00390
REAL *8 QINRAA,AINRAA DIP00400
REAL *8 CNCLNA,ELSGDB,ELSGDG,AWSGDB,AWSGDG DIP00410
REAL *8 SUMC,SUMAA,AVECAN,AVCAA,SAVE,SAVESR
REAL *4 RX(100),RY(100),RZ(100),FM(41,41),DMF(41,41)
REAL *4 AUXADB(NUMAUX),VATENA(NUMAUX)
INTEGER IAUXA(NUMAUX),LTMP(NUMCHN),MTMP(NUMCHN)
CHARACTER DATNAM*35, OUTNAM*35
COMMON /A/ DX,DY,NCOLX,NROWY,NEL,HZ,HL,ARAD,ZLOAD,ZCHAR DIP00460
COMMON /B/ NGEN,IGEN,THETAS,PHIS,IMUT,IBLTSL,IPATRN DIP00470
COMMON /D/ FGHZ,RLAMDA,IWL,IS,NSCANS DIP00480
COMMON /DEG/ THDR,THDMIN DIP00490
COMMON /PLT/ INEAR,IPLTM DIP00500
COMMON /XLYL/XL,YL DIP00510
COMMON /NEAR/ IANTX, IANTY, NPOWER, IPCONN, IPCONF, IPCUTF DIP00520
COMMON /NEAR2/ IPCFX, IPCFY, IPCFZ DIP00530
COMMON /P/ IN,YN,ZN,RLSX,RLSY,RLSZ,NCOLIN,NROWYN,NCOLZN DIP00540
COMMON /P2/ EDGET,ICOMB,PUNFLX,PUNFLY DIP00550
COMMON /CHEBY/ ICHEB,SLLDB DIP00560
COMMON /GROUND/ IGRNDP DIP00570
COMMON /NORM/ IENORM,BIGNDB DIP00580
COMMON /NORMAL/ INRNOR
COMMON /PCENTR/PCDXIN DIP00590
COMMON /WRITE/ IWR DIP00600
COMMON /SPLOSS/ ETASP,GAMSP
COMMON /DPLOSS/ ETADP,GAMDP

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COMMON /F/ FHZ,ER3,SIG3,TD3
COMMON /CIRCLE/ ICIRC,RADIUS,HLS
NAMELIST/DIPOLE/NCOLX,NROWY,HZIN,HLIN,ARADIN,ZLOAD,NGEN,IGEN,      DIP00610
1DXIN,DYIN,IMUT,NSCANS,THSD,PHSD,THSINC,IBLTSL,IPATRN,ER3,SIG3,TD3,
2NPHCT,PHCT,NTHTPT,ZCHAR,IWL,FCHZ,BWFHZ,NFREQ,THDR,THDMIN,ICIRC,
3XININ,YNIN,ZNIN,NCOLIN,NROWYN,NCOLZN,INEAR,IPRCOM,IANGLP,CRADIN,
4IANTX,IANTY,NPOWER,NFCOLX,NFROWY,IPCONN,IPCONF,IPCUTF,IPOL,HLSIN,
5IPCFX,IPCFY,IPCFZ,ITEK,IGRNDP,IGAIN,ICHEB,IWR,IENORM,BIGNDB,      DIP00660
6NXDUM,NYDUM,NPDX,EDGTDB,RLSXIN,RLSYIN,RLSZIN,ISLC,INUNIF,
7XFOCIN,ZFOCIN,XJAMIN,YJAMIN,ZJAMIN,IATTEN,AUXADB,INRNOR,
8NJAMS,PWRADB,PWRJDB,NAUX,IAUXA,IAUXB,ITLTPR,ITLTDP,
9IQUAN,INRERR,ELERDB,ELERDG,AWERDB,AWERDG,NBMOD,NBADWT,NRAN,SLADB DIP00700
C**NOTE: IF IWL=0 (INCHES), IWL=2 (METERS)
WRITE(6,2959)
2959 FORMAT(1X,'ENTER INPUT DATA FILE NAME (typ. sdipjamhyper.data)')
READ(5,*) DATNAM
OPEN(4,FILE=DATNAM,FORM='FORMATTED')
WRITE(6,3959)
3959 FORMAT(1X,'ENTER OUTPUT DATA FILE NAME (typ sdipjamhyper.output)')
READ(5,*) OUTNAM
OPEN(8,FILE=OUTNAM,FORM='FORMATTED')
CALL GETCP2(CPU1)
PI=3.141592654      DIP00710
DCR=PI/180.      DIP00720
DPDCR=DCR      DIP00730
CJ=(0.,1.)      DIP00740
CINMTR=0.0254
IGRNDP=1      DIP00750
IGAIN=0      DIP00760
ZLOAD=0.0      DIP00770
ICHEB=0      DIP00780
IWR=0      DIP00790
IENORM=1      DIP00800
EXCPCB=-1.0D0      DIP00810
IQUAN=0      DIP00820
NRAN=1      DIP00830
TILTPR=0.0      DIP00840
TILTDP=0.0      DIP00850
IATTEN=0      DIP00860
IPOL=1      DIP00870
ER3=1.0
SIG3=0.0
TD3=-1.0
ICIRC=0
CRADIN=0.0
HLSIN=0.0
ISLC=1
INUNIF=0
INRNOR=0
READ(4,DIPOLE)      DIP00880
IF(NFREQ.EQ.1) BWFHZ=0.0
IF(ISLC.EQ.0) WRITE(6,81100)
81100 FORMAT(1X,'FULLY ADAPTIVE ARRAY')
IF(ISLC.EQ.0.AND.ICHEB.EQ.0) INUNIF=1
IF(ICIRC.EQ.1) WRITE(6,7000)
7000 FORMAT(1X,'RING ARRAY GEOMETRY')
FHZ=FCHZ
IXZ=0

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IXY=0	
IF(NROWYN.EQ.1) IXZ=1	
IF(NCOLZN.EQ.1) IXY=1	
IF(IPOL.EQ.2) IPRCOM=0	DIP00890
IF(IPRCOM.EQ.0) WRITE(6,7898)	DIP00900
7898 FORMAT(1X,'NO PROBE COMPENSATION')	DIP00910
WRITE(6,9276)IGRNDP	DIP00920
9276 FORMAT(1X,'GROUND PLANE PARAMETER, IGRNDP=',I4)	DIP00930
CC DO 1615 IX=1,NAUX	DIP00940
CC IF(IATTEN.EQ.0) AUXADB(IX)=0.0	DIP00950
CC WRITE(6,2318)IX,AUXADB(IX)	DIP00960
C2318 FORMAT(1X,'IX,AUXADB(IX)=' ,I4,2X,F12.2)	DIP00970
CC VATENA(IX)=10.**(AUXADB(IX)/20.)	DIP00980
C1615 CONTINUE	DIP00990
IF(NJAMS.GT.1) WRITE(8,2009)XJAMIN(1),YJAMIN(1),ZJAMIN(1)	DIP01000
2009 FORMAT(1X,'XJAMIN(1),YJAMIN(1),ZJAMIN(1)=' ,3F12.3)	DIP01010
WRITE(6,6987) BWFHZ,NFREQ	DIP01020
6987 FORMAT(1X,'BWFHZ,NFREQ=' ,E12.5,2X,I5)	DIP01030
IF(ITEK.EQ.0)CALL COMPRS	DIP01040
IF(ITEK.EQ.1)CALL TEKALL(4014,480,0,1,0)	DIP01050
CC IF(INEAR.EQ.0) CALL PRNTDA	DIP01060
IF(IMUT.EQ.0) ZLOAD=1.0	DIP01070
IF(ITLTPR.EQ.1) TILTTPR=45.	DIP01080
IF(ITLTDP.EQ.1) TILTDP=45.	DIP01090
CTPR=COS(TILTTPR*DCR)	DIP01100
STPR=SIN(TILTTPR*DCR)	DIP01110
CTDP=COS(TILTDP*DCR)	DIP01120
STDP=SIN(TILTDP*DCR)	DIP01130
FGHZ=FCHZ/1.0E9	DIP01140
NEL=NCOLX*NROWY	DIP01150
RNEL=NEL	
XLIN=DXIN*(NCOLX-1)	DIP01160
YLIN=DYIN*(NROWY-1)	DIP01170
NACOLX=NCOLX-NPDX-2*NXDUM	DIP01180
NAROWY=NROWY-2*NYDUM	DIP01190
NAEL=NACOLX*NAROWY	
PCDXIN=NPDX*DXIN	DIP01200
NAUXP1=NAUX+1	DIP01220
NAUXP2=NAUX+2	DIP01230
IF(ISLC.EQ.1) NMAX=NAUXP1	
IF(ISLC.EQ.0) NMAX=NEL	
NMAXP1=NMAX+1	DIP01250
ELSGDB=ELERDB*SQRT(3.)	DIP01260
ELSGDG=ELERDG*SQRT(3.)	DIP01270
AWSGDB=AWERDB*SQRT(3.)	DIP01280
AWSGDG=AWERDG*SQRT(3.)	DIP01290
INITRN=1	DIP01300
IF(ISLC.EQ.0) THEN	
NAUX=NEL	
NAUXP1=NAUX+1	
NAUXP2=NAUX+2	
DO 79130 I=1,NEL	
IAUXA(I)=I	
WRITE(6,76767)I,IAUXA(I)	
76767 FORMAT(1X,'I,IAUXA(I)=' ,2I5)	
79130 CONTINUE	
ENDIF	
DO 1615 IX=1,NAUX	
IF(IATTEN.EQ.0) AUXADB(IX)=0.0	

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      WRITE(6,2318)IX,AUXADB(IX)
2318  FORMAT(1X,'IX,AUXADB(IX)=',I4,2X,F12.2)
      VATENA(IX)=10.**(AUXADB(IX)/20.)
1615  CONTINUE
30    CONTINUE
      NR=1
      IF(NGEN.EQ.1) NSCANS=0
      ICC=NEL
      ICC1=ICC
      IF(IBLTSL.EQ.1) ICC1=NROWY
CC    IF(IWL.EQ.1)GO TO 50
      WRITE(8,40)FGHZ
40    FORMAT(/,1X,'FGHZ=',F15.7)
C*****
C*****COMPUTE FREE SPACE LAMBDA*****
C*****ALL UNITS HAVE TO BE IN METERS
      RLAMDA=2.997925E10/FCHZ/2.54
C***PARAMETER CONVERSIONS TO PROPER UNITS
55    CONTINUE
      IF(IWL.EQ.2) GO TO 50
      DX=DXIN*CINMTR
      DY=DYIN*CINMTR
      HL=HLIN*CINMTR
      HLS=HLSIN*CINMTR
      ARAD=ARADIN*CINMTR
      HZ=HZIN*CINMTR
      RLSX=RLSXIN*CINMTR
      RLSY=RLSYIN*CINMTR
      RLSZ=RLSZIN*CINMTR
      XN=XNIN*CINMTR
      YN=YNIN*CINMTR
      ZN=ZNIN*CINMTR
      XFOC=XFOCIN*CINMTR
      ZFOC=ZFOCIN*CINMTR
      XL=XLIN*CINMTR
      YL=YLIN*CINMTR
      PCDX=PCDXIN*CINMTR
      RADIUS=CRADIN*CINMTR
50    CONTINUE
      WRITE(8,60)DX,DY,HL,ARAD
60    FORMAT(1X,'DX,DY,HL,ARAD=',2X,4F14.5)
C
C***COMPUTE CALIBRATION CONSTANTS (PHASE ONLY) TO
C***MAXIMIZE GAIN (FOCUS ANTENNA) TO NEAR FIELD RANGE
C
C***PHASE CENTER 'A' VOLTAGE EXCITATION
      XOA=-XL/2.+NXDUM*DX*(NACOLX-1)/2.*DX
      YP=0.0
      IF(ICIRC.EQ.0) WRITE(6,24690)
24690  FORMAT(1X,'CALLING NFDPI2')
      IF(ICIRC.EQ.0)
        2CALL NFDPI2(CTPR,STPR,CTDP,STDP,XFOC,YP,ZFOC,XOA,0,VA,VREFA)
      IF(ICIRC.EQ.1)
        2CALL NFDPC2(XFOC,YP,ZFOC,XOA,0,VA,VREFA)
C***SAVE INCIDENT VOLTAGES
      DO 65 IV=1,NEL
      VTA(IV)=VA(IV)
      WRITE(6,3757)IV,VTA(IV)
      WRITE(8,3757)IV,VTA(IV)

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DIP01310  
 DIP01320  
 DIP01330  
 DIP01340  
 DIP01350  
 DIP01360  
 DIP0137C  
 DIP01380  
 DIP01390

DIP01420

DIP01580  
 DIP01590  
 DIP01600  
 DIP01610  
 DIP01620  
 DIP01630  
 DIP01640  
 DIP01650  
 DIP01660  
 DIP01700

DIP01720  
 DIP01730  
 DIP01740  
 DIP01750

3757	FORMAT(1X,'IV,VTA=',I4,2X,2E12.4)	DIP01760
65	CONTINUE	DIP01770
	WRITE(6,9876)VTA(2)	DIP01780
9876	FORMAT(1X,'VTA(2)=' ,2E12.4)	DIP01790
	NB=NCOLX	DIP01800
	IDMB=NROWY	DIP01810
	IDM=NEL	DIP01820
	ICC=NEL	DIP01830
	IBLT=IBLTSL	DIP01840
	IDM1=IDM3	DIP01850
	IF(IBLT.EQ.0) IDM1=NEL	DIP01860
	I2=1	DIP01890
8889	CONTINUE	DIP02350
	CALL ZMATRIX(CTDP,STDP,IBLTSL,ICC1,ICC,CZ,Z)	
C***SOLVE SYSTEM OF EQUATIONS FOR THE UNKNOWN CURRENTS		
	IF(IBLT.EQ.1) GO TO 240	DIP02370
	ISYM=0	DIP02380
	I12=1	DIP02390
	WRITE(6,9876)VTA(2)	DIP02400
	WRITE(6,6110)	DIP02410
6110	FORMAT(1X,'CALL CROUT')	DIP02420
	CALL CROUT(Z,VA,ICC1,ICC,ISYM,IWR,I12,NEL)	DIP02430
	I12=2	DIP02440
	WRITE(6,9876)VTA(2)	DIP02450
	GO TO 255	DIP02460
240	IENTRY=4	DIP02470
	CALL BLTSOL(CZ,VA,PS,NCOLX,IDMB,IENTRY)	DIP02480
	IENTRY=3	DIP02490
255	WRITE(8,270)	DIP02500
270	FORMAT(1X,'CURRENTS')	DIP02510
	IF(NEL.LT.40) CALL CNORM(VA,NEL)	DIP02520
	WRITE(6,280)	DIP02530
280	FORMAT(1X,'AFTER CURRENTS SOLUTION')	DIP02540
C***VA ARE CURRENTS (AMPERES) NOW		DIP02550
C*		DIP02560
C***COMPUTE RECEIVED VOLTAGES		DIP02570
	DO 285 IC=1,NEL	DIP02580
	WRITE(6,7531)ZLOAD	DIP02590
7531	FORMAT(1X,'ZLOAD=',F12.5)	DIP02600
	WRITE(6,1134)IC,VTA(IC)	DIP02610
	VRECVA(IC)=VA(IC)*ZLOAD	DIP02620
	WRITE(6,1174)IC,VRECVA(IC)	DIP02630
1134	FORMAT(1X,'IC,VTA=',I4,2X,2E12.4)	DIP02640
1174	FORMAT(1X,'IC,VRECVA=',I4,2X,2E12.4)	DIP02650
	WRITE(6,1135)IC,VA(IC)	DIP02660
1135	FORMAT(1X,'IC,VA=',I4,2X,2E12.4)	DIP02670
	VRADB=20.*ALOG10(CABS(VRECVA(IC)))	DIP02680
	VRAPH=ATAN2(AIMAG(VRECVA(IC)),REAL(VRECVA(IC)))/DCR	DIP02690
C***COMPUTE CALIBRATION CONSTANTS (PHASE ONLY)		DIP02700
	ACALPH(IC)=-VRAPH	DIP02710
285	CONTINUE	DIP02720
	DO 7777 IC=1,NEL	DIP02730
	WRITE(6,6667)IC,ACALPH(IC)	DIP02740
CC	WRITE(8,6667)IC,ACALPH(IC)	DIP02750
6667	FORMAT(1X,'IC,ACALPH=',I4,2X,F10.2,' DEGS')	DIP02760
7777	CONTINUE	DIP02770
C***COMPUTE NEAR FIELD PATTERN OF FOCUSED ARRAY		DIP02780
C		DIP02790
C***COMPUTE BEAMFORMER WEIGHTS (I.E. TAPER)		DIP02800

IF(INUNIF.EQ.0)	
2CALL VRCVWT(NACOLX,NAROWY,NXDUM,NYDUM,EDGTDB,RWTA,RWTB)	DIP02810
DO 1199 IC=1,NEL	DIP02820
IF(INUNIF.EQ.1.AND.ISLC.EQ.0) RWTA(IC)=1./SQRT(RNEL)	
WRITE(6,5111)IC,RWTA(IC)	
WRITE(8,5111)IC,RWTA(IC)	
5111 FORMAT(1X,'IC,RWTA=',I4,2X,E12.5)	
1199 CONTINUE	DIP02850
DO 5333 KC=1,NEL	DIP02860
CWTA(KC,1)=RWTA(KC)*CEXP(CJ*ACALPH(KC)*DCR)	DIP02870
5333 CONTINUE	DIP02880
IF(IQUAN.EQ.1)	DIP02890
2CALL ADQUAN(NEL,CWTA,NBMOD,IRNERR,INITRN,ELSGDB,ELSGDG)	DIP02900
BIGWDB=-299.0	
DO 91020 I=1,NEL	
WRITE(6,61910)I,CWTA(I,1)	
WRITE(8,61910)I,CWTA(I,1)	
61910 FORMAT(1X,'I,CWTA(I,1)=',I4,2X,2E12.5)	
CWTADB=20.*DLOG10(CDABS(CWTA(I,1)))	
IF(CWTADB.GT.BIGWDB) BIGWDB=CWTADB	
91020 CONTINUE	
DO 91120 I=1,NEL	
CWTADB=20.*DLOG10(CDABS(CWTA(I,1)))-BIGWDB	
CWTADG=DATAN2(DIMAG(CWTA(I,1)),DREAL(CWTA(I,1)))/DCR	
WRITE(6,35990)I,CWTADB,CWTADG	
WRITE(8,35990)I,CWTADB,CWTADG	
35990 FORMAT(1X,'I=',I4,2X,'CWTADB,CWTADG=',1X,2F14.5)	
91120 CONTINUE	
INITRN=2	DIP02910
C***PERFORM NEAR FIELD SCAN WITH CW RADIATING DIPOLE	DIP02920
IF(INEAR.EQ.0) GO TO 390	DIP02930
WRITE(6,350)	DIP02940
WRITE(6,360)XNIN,YNIN,ZNIN,RLSXIN,RLSYIN,RLSZIN,NCOLXN,NROWYN,	DIP02950
2NCOLZN	DIP02960
WRITE(6,320)IWL	DIP02970
320 FORMAT(1X,'IWL=',I4)	DIP02980
WRITE(6,330)	DIP02990
330 FORMAT(1X,'CHANGE NEAR FIELD SCAN PARAMETERS?', ICHANG=1')	DIP03000
READ(5,*,END=370)ICHANG	DIP03010
IF(ICHANG.EQ.0) GO TO 370	DIP03020
WRITE(6,350)	DIP03030
350 FORMAT(1X,'XN,YN,ZN,RLSXIN,RLSYIN,RLSZIN,NCOLXN,NROWYN,NCOLZN=')	DIP03040
READ(5,*)XNIN,YNIN,ZNIN,RLSXIN,RLSYIN,RLSZIN,NCOLXN,NROWYN,NCOLZN	DIP03050
WRITE(6,360)XNIN,YNIN,ZNIN,RLSXIN,RLSYIN,RLSZIN,NCOLXN, JWYN,	DIP03060
2NCOLZN	DIP03070
360 FORMAT(1X,6F10.3,2X,3I5)	DIP03080
IF(IWL.EQ.2) GO TO 370	DIP03090
XN=XNIN*CINMTR	
YN=YNIN*CINMTR	
ZN=ZNIN*CINMTR	
RLSX=RLSXIN*CINMTR	
RLSY=RLSYIN*CINMTR	
RLSZ=RLSZIN*CINMTR	
370 CONTINUE	DIP03160
C**ALL DIMENSIONS IN METERS	
NELN=NCOLXN*NROWYN	DIP03180
NPTSN=NELN*NCOLZN	DIP03190
C***SET DEFAULT VALUES FOR DXN,DYN,DZN	
DXN=0.0	DIP03200



DYN=0.1	DIP03210
DZN=0.0	DIP03220
IF(NCOLXN.GT.1)DXN=RLSX/(NCOLXN-1)	DIP03230
IF(NROWYN.GT.1)DYN=RLSY/(NROWYN-1)	DIP03240
IF(NCOLZN.GT.1)DZN=RLSZ/(NCOLZN-1)	DIP03250
IC=0	DIP03260
BIGNDB=-299.0	DIP03270
DO 3000 ICOLZN=1,NCOLZN	DIP03280
ZPOS=ZN+DZN*(ICOLZN-1)	DIP03290
DO 3000 IROWYN=1,NROWYN	DIP03300
Y=YN+DYN*(IROWYN-1)	DIP03310
DO 3000 ICOLXN=1,NCOLXN	DIP03320
CALL GETCP2(CPU2)	
CPUSUB=CPU2-CPU1	
WRITE(6,7319)CPUSUB	
7319 FORMAT(1X,'CPU SUBTOTAL=',F14.2)	
IC=IC+1	DIP03330
X=XN+DXN*(ICOLXN-1)	DIP03340
XC(IC)=X	DIP03350
YC(IC)=Y	DIP03360
ZC(IC)=ZPOS	DIP03370
WRITE(6,6969)IC,XC(IC),YC(IC),ZC(IC)	DIP03410
6969 FORMAT(1X,'IC,XC,YC,ZC=',I4,2X,3F12.3)	DIP03420
IF(ICIRC.EQ.0)	
2CALL NFDPIX2(CTPR,STPR,CTDP,STDP,X,Y,ZPOS,0.0,0,VCW,VREFCW)	DIP03430
IF(ICIRC.EQ.1)	
2CALL NFDPC2(X,Y,ZPOS,0.0,0,VCW,VREFCW)	
IF(IMUT.EQ.0) GO TO 4255	DIP03440
C***SOLVE EACH SYSTEM OF EQUATIONS FOR THE UNKNOWN CURRENTS	DIP03450
IF(IBLT.EQ.1) GO TO 4040	DIP03460
I12=2	DIP03470
WRITE(6,6110)	DIP03480
CALL CROUT(Z,VCW,ICC1,ICC,ISYM,IWR,I12,NEL)	DIP03490
GO TO 4255	DIP03500
4040 IENTRY=3	DIP03510
CALL BLTSOL(CZ,VCW,PS,NCOLX,IDMB,IENTRY)	DIP03520
4255 CONTINUE	DIP03530
C***COMPUTE RECEIVED VOLTAGES FOR PRESENT SCAN	DIP03540
DO 3285 IIIC=1,NEL	DIP03550
VRECVX(IIIC)=VCW(IIIC)*ZLOAD	DIP03560
3285 CONTINUE	DIP03570
C***STORE AUX. CHANNEL VOLTAGES	DIP03580
DO 1681 IAX=1,NAUX	DIP03590
C**MODIFICATION TO INCLUDE AUX. ATTEN.	DIP03600
VAXCWA(IAX,IC)=VRECVX(IAUXA(IAX))*VATENA(IAX)	DIP03610
CC WRITE(6,3231)IAX,IC,XC(IC),VAXCWA(IAX,IC)	DIP03620
3231 FORMAT(1X,'IAX,IC,XC,VAXCWA(IAX,IC)=' ,2I4,2X,F12.3,2X,2E12.5)	DIP03630
1681 CONTINUE	DIP03640
C***PERFORM BEAM FORMATION	DIP03650
CSUMA=(0.,0.)	DIP03660
DO 5444 KC=1,NEL	DIP03670
CSUMA=CSUMA+VRECVX(KC)*CWTA(KC,1)	DIP03680
5444 CONTINUE	DIP03690
VXA=CSUMA	DIP03700
IF(CABS(VXA).EQ.0.)VXA=(1.E-10,0.)	DIP03710
VXADB(IC)=20.*ALOG10(CABS(VXA))	DIP03720
IF(VXADB(IC).GT.BIC**DB) BIGNDB=VXADB(IC)	DIP03730
VXAPH(IC)=ATAN2(AIMAG(VXA),REAL(VXA))/DCR	DIP03740
VXMANA(IC)=10.*(VXADB(IC)/20.)*CEXP(CJ+VXAPH(IC)*DCR)	DIP03750
CC WRITE(6,4457)IC,VXMANA(IC)	DIP03760

CC	WRITE(6,4457)IC,VXMANA(IC)	DIP03760
4457	FORMAT(1X,'IC,VXMANA=',I4,2X,2E12.5)	DIP03770
	WRITE(6,6429)IC,IC(IC),VIADB(IC)	DIP03780
6429	FORMAT(1X,'IC,X,VIADB=',I4,2X,F10.2,2X,F12.2)	DIP03790
3000	CONTINUE	DIP03800
	IF(IENORM.EQ.0) GO TO 2500	DIP03810
	WRITE(6,3765)BIGNDB	DIP03820
3765	FORMAT(1X,'BIGNDB=',F12.2)	DIP03830
	DO 3020 IC=1,NPTSN	DIP03840
CC	WRITE(6,3343)IC,VIADB(IC)	DIP03850
	VIADB(IC)=VIADB(IC)-BIGNDB	DIP03860
CC	WRITE(6,3343)IC,VIADB(IC)	DIP03870
3020	CONTINUE	DIP03880
2500	WRITE(6,3030)	DIP03890
3030	FORMAT(1X,'WANT TO PLOT NEAR FIELD CUTS, IPLOTN=1')	DIP03900
	READ(5,*)IPLOTN	DIP03910
	C***NEXT LINE ADDED TO AVOID RUN TIME ERROR	DIP03920
	IF(IPCONN.EQ.1) IPLOTN=0	DIP03930
	IF(IPCONN.EQ.0) THEN	
	WRITE(30,18889)	
	WRITE(30,18888)XN,NCOLXN,DYN,ZN,NCOLZN,DZN	
	WRITE(30,4547)	
4547	FORMAT(1X,'IZ,IX,VIADB(IC)')	
	ENDIF	
	IPP=0	
	DO 7788 IZ=1,NCOLZN	
	DO 7788 IY=1,NROWYN	
	DO 7788 IX=1,NCOLXN	
	IPP=IPP+1	
CC	DO 7788 IPP=1,NPTSN	DIP03950
CC	WRITE(6,3343)IPP,VIADB(IPP)	DIP03960
3343	FORMAT(1X,'IPP,VIADB=',I4,2X,F12.2)	DIP03970
	IF(IPCONN.EQ.0) WRITE(30,*) IZ,IX,VIADB(IPP)	
7788	CONTINUE	DIP03980
3040	IF((NCOLXN.GT.1.OR.NROWYN.GT.1).AND.IPLOTN.EQ.1)	DIP03990
	1CALL PLOTTR(NCOLXN,NROWYN,NCOLZN,IC,YC,ZC,NPTSN,VIADB,VXAPH,	DIP04000
	2VIADB,VXAPH)	DIP04010
	IF(NELN.EQ.1.AND.IPLOTN.EQ.1)	DIP04020
	1CALL PLOTAX(NPTSN,ZC,VIADB,VXAPH,VIADB,VXAPH)	DIP04030
	IF(IPCONN.EQ.0) GO TO 3939	DIP04040
	C***THIS SECTION FOR CONTOUR PLOTS	DIP04050
	NCLIN2=NCOLXN+2	DIP04060
	NRWYN2=NROWYN+2	DIP04070
	NCLZN2=NCOLZN+2	
	DO 3777 IX=1,NCOLXN	DIP04080
	RX(IX)=(XN+DXN*(IX-1))/CINMTR	
3777	CONTINUE	DIP04100
	DO 3008 IY=1,NROWYN	DIP04110
	RY(IY)=(YN+DYN*(IY-1))/CINMTR	
3008	CONTINUE	DIP04130
	DO 3009 IZ=1,NCOLZN	
	RZ(IZ)=(ZN+DZN*(IZ-1))/CINMTR	
3009	CONTINUE	
	IC=0	DIP04140
	IF(IXZ.EQ.1) WRITE(30,18889)	
18889	FORMAT(1X,'XN,NCOLXN,DYN,ZN,NCOLZN,DZN=')	
	IF(IXZ.EQ.1) WRITE(30,18888)XN,NCOLXN,DYN,ZN,NCOLZN,DZN	
18888	FORMAT(1X,E11.5,I5,2X,E14.5,2X,E14.5,I5,2X,E14.5)	
	IF(IXZ.EQ.1) WRITE(30,4546)	

4546	FORMAT(IX,'IZ,IX,FM(IZ,IX)')	
	DO 3022 IZ=1,NCOLZN	
	DO 3022 IY=1,NROWYN	DIP04150
	DO 3022 IX=1,NCOLXN	DIP04160
	IC=IC+1	DIP04170
	IF(IXY.EQ.1) FM(IY,IX)=VXADB(IC)	
	IF(IXZ.EQ.1) FM(IZ,IX)=VXADB(IC)	
	IF(IXZ.EQ.1.AND.IPCONN.EQ.1) WRITE(30,*) IZ,IX,FM(IZ,IX)	
3022	CONTINUE	DIP04190
	IF(IXY.EQ.1)	
	2CALL PLCONT(NCOLXN,NROWYN,NCLXN2,NRWYN2,IX,RY,FM,DMF,-50.,	DIP04200
	310.,5,1)	DIP04210
	IF(IXZ.EQ.1)	
	2CALL PLCONT(NCOLXN,NCOLZN,NCLXN2,NCLZN2,IX,RZ,FM,DMF,-50.,	
	310.,5,1)	
3939	CONTINUE	DIP04220
CC	WRITE(25,*)NCOLXN	DIP04470
	DO 1767 IDDD=1,NCOLXN	DIP04480
CC	WRITE(25,*)VXADB(IDDD)	
1767	CONTINUE	DIP04500
	WRITE(6,3050)	DIP04510
3050	FORMAT(IX 'PLOT NEAR FIELD AGAIN?, IPLA=1')	DIP04520
	READ(5,*)IPLA	DIP04530
	IF(IPLA.EQ.1) GO TO 3040	DIP04540
390	CONTINUE	DIP04550
	ISTOP=0	DIP04560
	IF(ISTOP.EQ.1) GO TO 9999	DIP04570
C***	CALL PRNTDA (PRINT PARAMETERS)	DIP04580
C370	CALL PRNTDA	DIP04590
	IF(IPATRN.EQ.0) GO TO 440	DIP04630
410	WRITE(6,420)	DIP04640
420	FORMAT(IX,'ISYMBL FOR PLOTTING, LT. 0 THEN NOT USED')	DIP04650
	READ(5,*)ISYMBL	DIP04660
	WRITE(6,430)	DIP04700
430	FORMAT(IX,'WANT TO PLOT PATTERNS AGAIN?, IPFNA=1')	DIP04710
	READ(5,*)IPFNA	DIP04720
	IF(IPFNA.EQ.1) GO TO 410	DIP04730
440	CONTINUE	DIP04740
C***	THIS SECTION FOR COVARIANCE MATRIX COMPUTATION	DIP04750
	IF(NJAMS.EQ.0) GO TO 9999	
	DO 7999 ICH=1,NMAX	DIP04770
	DO 7999 JCH=1,NMAX	DIP04780
	COVNF(ICH,JCH)=DCMLPLX(0.0D0,0.0D0)	DIP04790
7999	CONTINUE	DIP04800
8888	IF(NJAMS.EQ.0) GO TO 4444	DIP04810
C***	THIS SECTION FOR JAMMER COVARIANCE MATRIX	DIP04820
	FMINHZ=FCHZ-BWFBZ/2.	DIP04830
	DELFHZ=0.0	
	IF(NFREQ.GT.1) DELFHZ=BWFBZ/(NFREQ-1)	
	DO 600 IFR=1,NFREQ	DIP04850
	FHZ=FMINHZ+DELFHZ*(IFR-1)	DIP04860
	FGHZ=FHZ/1.0E9	DIP04870
C***	COMPUTE FREE SPACE WAVELENGTH AT EACH FREQUENCY	
	RLAMDA=2.997925E10/FHZ/2.54	
C***	NOTE: GAMMA= ALPHA +J BETA	
C***	AND RLAMDA=2 PI/ BETA (REF. HAYT PG. 334)	
C***	THUS NEED TO COMPUTE GAMMA, AND ETA FOR EACH FREQ.	
	IF(IWL.EQ.2) GO TO 8789	
	DX=DXIN+CINMTR	

DY=DIIN+CINMTR	
HL=HLIN+CINMTR	
ARAD=ARADIN+CINMTR	
HZ=HZIN+CINMTR	
8789 CONTINUE	
CALL ZMATRIX(CTDP,STDP,IBLTSL,ICC1,ICC,CZ,Z)	DIP04940
C***COMPUTE ELEMENT INDUCED VOLTAGES DUE TO JAMMER SOURCES	DIP04950
CALL VJAMMR(NJAMS,NEL,PWRJDB,ICC1,ICC,PS,CZ,Z,CWTA	DIP04960
1,NB,IDMB,NAUX,IAUXA,ZLOAD,IJAMIN,YJAMIN,ZJAMIN,	DIP04970
2IFR,NFREQ,CTPR,STPR,CTDP,STDP,VMAJMA,VAUXJA)	DIP04980
WRITE(6,1234)IFR,VMAJMA(1,IFR),VAUXJA(1,1,IFR)	DIP04990
WRITE(8,1234)IFR,VMAJMA(1,IFR),VAUXJA(1,1,IFR)	DIP05000
1234 FORMAT(1X,'IFR,VMAJMA,VAUXA=',I4,2X,4E11.4)	DIP05010
600 CONTINUE	DIP05020
C***FORM RECEIVED VOLTAGE MATRIX	DIP05030
C***VRECVH(MAIN A, AUX A1, AUX A2,... AUX AN :)	
DO 9001 IJAM=1,NJAMS	DIP05050
DO 9002 IFR=1,NFREQ	DIP05060
IF(ISLC.EQ.1) VCHA(1,IFR)=VMAJMA(IJAM,IFR)	
CC WRITE(6,6789)IJAM,IFR,VMAJMA(IJAM,IFR)	DIP05080
6789 FORMAT(1X,'IJAM,IFR,VMAJMA(IJAM,IFR)=',2I4,2X,2E12.5)	DIP05090
DO 9003 IA=1,NAUX	DIP05100
IAP1=IA+1	DIP05110
IF(ISLC.EQ.1) VCHA(IAP1,IFR)=VAUXJA(IA,IJAM,IFR)*VATENA(IA)	
IF(ISLC.EQ.0) VCHA(IA,IFR)=VAUXJA(IA,IJAM,IFR)*VATENA(IA)	
WRITE(6,8876)IJAM,IFR,IA,VAUXJA(IA,IJAM,IFR)	
WRITE(8,8876)IJAM,IFR,IA,VAUXJA(IA,IJAM,IFR)	
8876 FORMAT(1X,'IJAM,IFR,IA,VAUXJA=',3I4,2X,2E12.4)	DIP05150
9003 CONTINUE	DIP05160
9002 CONTINUE	DIP05170
DO 5555 KKK=1,4	DIP05180
DO 5555 LLL=1,NFREQ	DIP05190
CCC WRITE(6,6655)KKK,LLL,VCHA(KKK,LLL)	DIP05200
5555 CONTINUE	DIP05210
WRITE(6,5533)	DIP05220
5533 FORMAT(1X,'NOW COMPUTE JAMMER COVARIANCE MATRIX')	DIP05230
C***COMPUTE COVARIANCE MATRIX FOR JTH JAMMER SOURCE	DIP05240
IF(NFREQ.GT.1) CALL COVSWC(VCHA,VCHA,NMAX,NFREQ,BWPHZ,COVAAJ)	
DO 9005 ICH=1,NMAX	
DO 9005 JCH=1,NMAX	
COVNF(ICH,JCH)=COVNF(ICH,JCH)+COVAAJ(ICH,JCH)	DIP05280
CC WRITE(6,2299)ICH,JCH,COVNF(ICH,JCH)	DIP05290
9005 CONTINUE	DIP05300
9001 CONTINUE	DIP05310
C***ADD RECEIVER NOISE TO DIAGONAL ELEMENTS	DIP05320
4444 DO 8006 ICH=1,NMAX	DIP05330
COVNF(ICH,ICH)=COVNF(ICH,ICH)+1.0D0	DIP05340
8006 CONTINUE	DIP05350
DO 2727 I=1,NMAX	DIP05360
DO 2727 J=1,NMAX	DIP05370
IF(CDABS(COVNF(I,J)).EQ.0.0D0) GO TO 2727	DIP05380
CNDB=10.*DLOG10(CDABS(COVNF(I,J)))	DIP05390
PREALN=DREAL(COVNF(I,J))	DIP05400
PIMAGN=DIMAG(COVNF(I,J))	DIP05410
PHASEN=DATAN2(PIMAGN,PREALN)/DCR	DIP05420
WRITE(8,4411)I,J,CNDB,PHASEN	DIP05430
IF(I.EQ.1)WRITE(6,4411)I,J,CNDB,PHASEN	DIP05440
4411 FORMAT(1X,'I,J,CNDB,PHASEN=',2I4,2X,2F12.2)	DIP05450
2727 CONTINUE	DIP05460

C***COMPUTE COVARIANCE MATRIX INVERSE	DIP05470
DO 8007 ICH=1,NMAX	DIP05480
DO 8007 JCH=1,NMAX	DIP05490
COVNF(I,ICH,JCH)=COVNF(I,ICH,JCH)	DIP05500
8007 CONTINUE	DIP05510
CALL DCMINV(COVNF,I,LTMP,MTMP,NMAX,NMAX)	DIP05520
C***CHECK MATRIX INVERSION ACCURACY (CINVERSE=C-I)	DIP05530
CALL CMMULT(COVNF,I,COVNF,NMAX,NMAX,NMAX,CINVCN)	DIP05540
DO 8008 ICH=1,NMAX	DIP05550
DO 8008 JCH=1,NMAX	DIP05560
IF(ICH.EQ.1)WRITE(6,8009)ICH,JCH,CINVCN(ICH,JCH)	DIP05570
8009 FORMAT(1X,'ICH,JCH,CINVCN=',2I4,2X,2E12.5)	DIP05580
8008 CONTINUE	DIP05590
C***COMPUTE EIGENVALUES (ALSO EIGENVECTORS AND PERFORMANCE INDEX)	DIP05600
IJOB=2	DIP05610
CALL EIGCC(COVNF,NMAX,NMAX,IJOB,EIGVAN,EIGVEN,NMAX,WKE,IER)	DIP05620
WRITE(6,155)IER	DIP05630
155 FORMAT(1X,'AFTER COMPUTE EIGENVALUES, IER=',I5)	DIP05640
DO 200 I=1,NMAX	DIP05650
WRITE(6,300)I,EIGVAN(I)	DIP05660
300 FORMAT(1X,'I,EIGVAN=',2X,I4,2E10.3)	DIP05670
200 CONTINUE	DIP05680
DO 205 I=1,NMAX	DIP05690
EVLDBN=10.*DLOG10(CDABS(EIGVAN(I)))	DIP05710
WRITE(8,207)I,EVLDBN	DIP05720
WRITE(6,207)I,EVLDBN	DIP05730
207 FORMAT(1X,'I,EVLDBN=',I4,2X,2F12.3)	DIP05740
205 CONTINUE	DIP05750
C*** CALL PRNTDA	DIP05760
C***FILL-IN SIDELOBE CANCELLER QUIESCENT WEIGHTS	DIP05770
DO 8985 I=1,NMAX	DIP05780
WQSLC(I,1)=DCMPLX(0.0D0,0.0D0)	DIP05790
8985 CONTINUE	DIP05800
WQSLC(1,1)=DCMPLX(1.0D0,0.0D0)	DIP05810
DO 7769 I=1,NMAX	DIP05820
WRITE(6,1212)I,WQSLC(I,1)	DIP05830
WRITE(8,1212)I,WQSLC(I,1)	DIP05840
1212 FORMAT(1X,'I,WQSLC=',I4,2X,2E12.5)	DIP05850
7769 CONTINUE	DIP05860
C***COMPUTE QUIESCENT INR	DIP05870
IF(ISLC.EQ.1) CALL INRTIO(WQSLC,COVNF,NMAX,WTCTR,CMPROD,QINRDB)	
IF(ISLC.EQ.0) CALL INRTIO(CWTA,COVNF,NMAX,WTCTR,CMPROD,QINRDB)	
QINRAA=10.*DLOG10(CDABS(COVNF(1,1)))	DIP05890
C***COMPUTE AVERAGE CANCELLATION	
SUMC=0.0	DIP05910
SUMAA=0.0	DIP05920
DO 1829 IR=1,NRAN	DIP05930
C***ZERO-OUT ADAPTIVE WEIGHTS INITIALLY	DIP05940
DO 57 I=1,NMAX	DIP05950
WAN(I,1)=DCMPLX(0.0D0,0.0D0)	DIP05960
57 CONTINUE	DIP05970
C***COMPUTE ADAPTIVE ARRAY WEIGHTS	DIP05980
IF(ISLC.EQ.1) CALL CMMULT(COVNF,WQSLC,NMAX,NMAX,1,WAN)	
IF(ISLC.EQ.0) CALL CMMULT(COVNF,CWTA,NMAX,NMAX,1,WAN)	
C***QUANTIZE AND RANDOMIZE ADAPTIVE WEIGHT SETTINGS	DIP06000
IF(IQUAN.EQ.1.AND.NBADWT.LT.20)	DIP06010
2CALL ADQUAN(NMAX,WAN,NBADWT,IRNERR,INITRN,AWSGDB,AWSGDG)	DIP06020
C***NORMALIZE FULLY ADAPTIVE WEIGHTS	
IF(ISLC.EQ.0) THEN	

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        SAVE=0.000
        DO 33345 I=1,NEL
        SAVE=SAVE+CDABS(WAN(I,1))*2
33345    CONTINUE
        SAVESR=DSQRT(SAVE)
        DO 44456 I=1,NEL
        WAN(I,1)=WAN(I,1)/SAVESR
        WANDB=20.*DLOG10(CDABS(WAN(I,1)))
        IF(IR.EQ.1) WRITE(6,3599)I,WANDB
        IF(IR.EQ.1) WRITE(8,3599)I,WANDB
3599    FORMAT(1X,'I=',I4,2X,'WANDB=',1X,F12.3)
44456    CONTINUE
        ENDIF
C***TO PRINT NORMALIZED WEIGHTS
        BIGWDB=-299.0
        DO 9102 I=1,NMAX
        IF(IR.EQ.1) WRITE(6,6191)I,WAN(I,1)
        IF(IR.EQ.1) WRITE(8,6191)I,WAN(I,1)
6191    FORMAT(1X,'I,WAN(I,1)=',I4,2X,2E12.5)
        WANDBM=20.*DLOG10(CDABS(WAN(I,1)))
        IF(WANDBM.GT.BIGWDB) BIGWDB=WANDBM
9102    CONTINUE
        DO 9112 I=1,NMAX
        WANDB=20.*DLOG10(CDABS(WAN(I,1)))-BIGWDB
        WANDG=DATAN2(DIMAG(WAN(I,1)),DREAL(WAN(I,1)))/DCR
        IF(IR.EQ.1) WRITE(6,35991)I,WANDB,WANDG
        IF(IR.EQ.1) WRITE(8,35991)I,WANDB,WANDG
35991    FORMAT(1X,'I=',I4,2X,'WANDB,WANDG=',1X,2F14.5)
9112    CONTINUE
C***COMPUTE ADAPTED INR
        CALL INRTIO(WAN,COVNF,NMAX,WTCTR,CMPROD,AINRDB)
C***COMPUTE CANCELLATION
        CANCDB=AINRDB-QINRDB
        WRITE(6,3007)QINRDB,AINRDB,CANCDB
        WRITE(8,3007)QINRDB,AINRDB,CANCDB
3007    FORMAT(1X,'INR= QUI,ADAP ,CANCEL=',2X,3F10.3,2X,' DB')
        SUMC=SUMC+CANCDB
C***COMPUTE ADAPTED INR CH. A
        DO 2255 I=1,NMAX
        WANDMA(I,1)=WAN(I,1)
        IF(I.GT.NMAX) WANDMA(I,1)=(0.000,0.000)
2255    CONTINUE
        CALL INRTIO(WANDMA,COVNF,NMAX,WTCTR,CMPROD,AINRAA)
C***CANCELLATION CH. A
        CNCLNA=AINRAA-QINRAA
        WRITE(6,3738)QINRAA,AINRAA,CNCLNA
        WRITE(8,3739)QINRAA,AINRAA,CNCLNA
3738    FORMAT(1X,'SIDELOBE CANCELLER CH. A INR= QUI,ADAP,CAN=',2X,3F10.3)
        SUMAA=SUMAA+CNCLNA
1829    CONTINUE
        AVECAN=SUMC/NRAN
        WRITE(6,4456)CANCDB,NRAN,AVECAN
4456    FORMAT(1X,'CANCDB,NRAN,AVECAN=',F12.5,2X,I5,2X,F12.5)
        WRITE(8,4456)CANCDB,NRAN,AVECAN
        AVECAA=SUMAA/NRAN
        WRITE(6,2220)AVECAA
        WRITE(8,2220)AVECAA
2220    FORMAT(1X,'AVE. CANEL. CH. A, =',2X,F12.5)
C***SECTION TO COMPUTE ADAPTIVE ARRAY RADIATION PATTERNS

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DIP06030
DIP06040
DIP06050
DIP06100
DIP06110
DIP06060
DIP06070
DIP06080
DIP06090
DIP06130
DIP06170
DIP06180
DIP06190
DIP06200
DIP06210
DIP06220
DIP06230
DIP06240
DIP06250
DIP06260
DIP06270
DIP06280
DIP06290
DIP06300
DIP06310
DIP06320
DIP06330
DIP06340
DIP06350
DIP06370
DIP06380
DIP06390
DIP06400
DIP06410
DIP06420
DIP06430
DIP06440
DIP06450
DIP06460
DIP06470

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CC	IF(INEAR.EQ.0.OR.IANGLP.EQ.0) GO TO 9990	DIP06480
	IF(INEAR.EQ.0) GO TO 9990	DIP06490
	BIGADB=-299.	DIP06500
	IC=0	DIP06510
	DO 8919 IZ=1,NCOLZN	
	DO 8919 IY=1,NROWYN	DIP06520
	DO 8919 IX=1,NCOLXN	DIP06530
	IC=IC+1	DIP06540
	CSUMA=(0.,0.)	DIP06550
	IF(ISLC.EQ.1) CSUMA=CSUMA+DCONJG(WAN(1,1))*VXMANA(IC)	
	DO 7921 IAX=1,NAUX	DIP06570
	IAXP1=IAX+1	DIP06580
	IF(ISLC.EQ.1) CSUMA=CSUMA+DCONJG(WAN(IAXP1,1))*VAICWA(IAX,IC)	
	IF(ISLC.EQ.0) CSUMA=CSUMA+DCONJG(WAN(IAX,1))*VAICWA(IAX,IC)	
7921	CONTINUE	DIP06610
	IF(CABS(CSUMA).EQ.0.) CSUMA=(1.E-10,0.)	DIP06620
	PCHADB(IC)=20.*ALOG10(CABS(CSUMA))	DIP06630
	IF(PCHADB(IC).GT.BIGADB) BIGADB=PCHADB(IC)	DIP06650
CC	WRITE(6,4999)IC,PCHADB(IC)	DIP06660
8919	CONTINUE	DIP06670
	C***NORMALIZE ADAPTIVE PATTERNS	DIP06680
	IF(IXZ.EQ.1) WRITE(31,18889)	
	IF(IXZ.EQ.1) WRITE(31,18888)XN,NCOLXN,DXN,ZN,NCOLZN,DZN	
	IF(IXZ.EQ.1) WRITE(31,4546)	
	IC=0	DIP06690
	DO 3459 IZ=1,NCOLZN	
	DO 3459 IY=1,NROWYN	DIP06700
	DO 3459 IX=1,NCOLXN	DIP06710
	IC=IC+1	DIP06720
	PCHADB(IC)=PCHADB(IC)-BIGADB	DIP06730
	IF(IPCONN.EQ.0) WRITE(31,*)IZ,IX,PCHADB(IC)	
	IF(IPCONN.EQ.0) GO TO 3459	
	IF(IXY.EQ.1) FM(IY,IX)=PCHADB(IC)	
	IF(IXZ.EQ.1) FM(IZ,IX)=PCHADB(IC)	
	IF(IXZ.EQ.1.AND.IPCONN.EQ.1) WRITE(31,*) IZ,IX,FM(IZ,IX)	
3459	CONTINUE	DIP06780
	WRITE(25,*)NCOLXN	DIP06800
	DO 1879 IDDD=1,NCOLXN	DIP06810
	WRITE(25,*)PCHADB(IDDD)	
1879	CONTINUE	DIP06830
	IF((NCOLXN.GT.1.OR.NROWYN.GT.1).AND.IPLOTN.EQ.1.AND.IANGLP.EQ.0)	DIP06840
	2CALL PLOTTR(NCOLXN,NROWYN,NCOLZN,XC,YC,ZC,NPTSN,PCHADB,PCHADB,	DIP06850
	3PCHADB,PCHADB)	DIP06860
	IF(IPCONN.EQ.1.AND.IXY.EQ.1)	
	2CALL PLCONT(NCOLXN,NROWYN,NCLXN2,NRWYN2,RX,RY,	
	3FM,DMF,-50.,10.,5,1)	DIP06880
	IF(IPCONN.EQ.1.AND.IXZ.EQ.1)	
	2CALL PLCONT(NCOLXN,NCOLZN,NCLXN2,NCLZN2,RX,RZ,	
	3FM,DMF,-50.,10.,5,1)	
9990	CONTINUE	DIP06890
9999	CONTINUE	DIP06900
	CALL DONEPL	DIP06910
	CALL GETCP2(CPUL)	
	CPUTOT=CPUL-CPU1	
	WRITE(6,2006)CPUTOT	
2006	FORMAT(1X,'TOTAL CPU TIME=',F15.2)	
	STOP	DIP06920
	END	DIP06930
	C***SUBROUTINE TO COMPUTE IMPEDANCE MATRIX	DIP07720

SUBROUTINE ZMATRIX(CTDP,STDP,IBLTSL,ICC1,ICC,CZ,Z)	DIP07730
COMPLEX Z(ICC1,ICC),CZ(1)	DIP07740
COMMON/A/DX,DY,NCOLX,NROWY,NEL,HZ,HL,ARAD,ZLOAD,ZCHAR	DIP07750
COMMON /GROUND/ IGRNDP	DIP07760
COMMON /CIRCLE/ ICIRC,RADIUS,HLS	
NB=NCOLX	DIP07770
IDMB=NROWY	DIP07780
C***COMPUTE MUTUAL IMPEDANCES Z(1,1),Z(1,2),Z(1,3),...,Z(1,NEL).	DIP07790
CC CALL RGDZMN(IGRNDP,ICC1,ICC,Z)	DIP07800
CC CALL RGDZAB(CTDP,STDP,IGRNDP,ICC1,ICC,Z)	DIP07810
IF(ICIRC.EQ.0) CALL RGDZA2(CTDP,STDP,IGRNDP,ICC1,ICC,Z)	
IF(ICIRC.EQ.1) CALL CADZA2(CTDP,STDP,IGRNDP,ICC1,ICC,Z)	
WRITE(8,10) NEL,NCOLX,NROWY	DIP07830
10 FORMAT(1X,'NEL,NCOLX,NROWY=',3I5)	DIP07840
ICOUNT=0	DIP07850
DO 20 I=1,NCOLX	DIP07860
DO 20 J=1,NROWY	DIP07870
ICOUNT=ICOUNT+1	DIP07880
WRITE(6,80) I,J,Z(1,ICOUNT)	DIP07890
80 FORMAT(1X,'I,J,Z(1,ICOUNT)=' ,2I4,2X,2E12.5)	DIP07900
20 CONTINUE	DIP07910
IDM=NEL	DIP07920
ICC=NEL	DIP07930
C***FILL THE IMPEDANCE MATRIX	DIP07940
IF(NCOLX.LE.1) GO TO 70	DIP07950
IBLT=IBLTSL	DIP07960
IDM1=IDMB	DIP07970
IF(IBLT.EQ.0) IDM1=NEL	DIP07980
IF(NROWY.GT.1) GO TO 40	DIP07990
C***FILL TOEPLITZ MATRIX	DIP08000
DO 30 I=2,NEL	DIP08010
DO 30 J=I,NEL	DIP08020
K=1+J-I	DIP08030
Z(I,J)=Z(1,K)	DIP08040
30 CONTINUE	DIP08050
GO TO 50	DIP08060
40 CALL BTOEPL(IBLT,NB,IDMB,IDM1,IDM,Z)	DIP08070
50 CONTINUE	DIP08080
IF(IBLT.EQ.0) GO TO 70	DIP08090
DO 60 I=1,IDMB	DIP08100
DO 60 J=1,IDM	DIP08110
IC=(J-1)*IDMB+I	DIP08120
CZ(IC)=Z(I,J)	DIP08130
CC WRITE(8,7878)I,J,Z(I,J)	DIP08140
7878 FORMAT(1X,'I,J,Z(I,J)=' ,2I4,2X,2E12.5)	DIP08150
60 CONTINUE	DIP08160
70 CONTINUE	DIP08170
RETURN	DIP08180
END	DIP08190
C***SUBROUTINE TO COMPUTE RECEIVE BEAMFORMER WEIGHTS	DIP09150
SUBROUTINE VRCVWT(NACOLX,NAROWY,NXDUM,NYDUM,EDGTDB,WA,WB)	DIP09160
DIMENSION WA(1),WB(1)	DIP09170
DIMENSION WT(180)	DIP09180
COMMON/A/DX,DY,NCOLX,NROWY,NEL,HZ,HL,ARAD,ZLOAD,ZCHAR	DIP09200
COMMON /CHEBY/ ICHEB,SLLDB	DIP09210
PI=3.141592654	DIP09220
TFI=2.*PI	DIP09230
DCR=PI/180.	DIP09240
CC SLLDB=40.	DIP09250



TAP=10.*(EDGTDB/20.)	DIP09260
WRITE(6,*)TAP	DIP09270
AMP=(1.-TAP)/2.	DIP09280
NPDIX=NCOLX-NACOLX-2*NXDUM	DIP09290
AXL=DX*(NACOLX-1)	DIP09300
AYL=DY*(NAROWY-1)	DIP09310
IF(TAP.NE.1.0)FX=AXL/2.*PI/ACOS(TAP)	DIP09320
IF(TAP.NE.1.0)FY=AYL/2.*PI/ACOS(TAP)	DIP09330
WRITE(6,20)	DIP09340
20 FORMAT(1X,'BEFORE CALL CHEBWT')	DIP09350
WRITE(6,30)SLADB	DIP09360
30 FORMAT(1X,'SLADB=',2X,F10.2)	DIP09370
IF(ICHEB.EQ.1)CALL CHEBWT(NACOLX,SLADB,WT,RLOSS)	DIP09380
WRITE(6,40)	DIP09390
40 FORMAT(1X,'AFTER CHEBWT')	DIP09400
DO 1000 IC=1,NEL	DIP09410
WA(IC)=0.0	DIP09420
WB(IC)=0.0	DIP09430
1000 CONTINUE	DIP09440
C***COMPUTE EFFECTIVE DIPOLE CENTER COORDS. FOR BOTH PHASE CENTERS	DIP09450
XO=-AXL/2.	DIP09460
YO=-AYL/2.	DIP09470
IC=0	DIP09480
DO 80 I=1,NACOLX	DIP09490
DO 80 J=1,NAROWY	DIP09500
IC=IC+1	DIP09510
X=XO+DX*(I-1)	DIP09520
Y=YO+DY*(J-1)	DIP09530
TAPERX=1.0	DIP09540
TAPERY=1.0	DIP09550
IF(ICHEB.EQ.1) GO TO 70	DIP09560
IF(TAP.NE.1.0)TAPERX=COS(PI*X/FX)	DIP09570
IF(TAP.NE.1.0.AND.FY.NE.0.0)TAPERY=COS(PI*Y/FY)	DIP09580
60 TAPER=TAPERX*TAPERY	DIP09590
WT(IC)=TAPER	DIP09600
70 CONTINUE	DIP09610
80 CONTINUE	DIP09620
C***TRANSFORM FROM SUB-APERTURES TO FULL ARRAY	DIP09630
IBGNA=NXDUM*NROWY+NYDUM	DIP09640
IBGNB=IBGNA+NPDIX*NROWY	DIP09650
IC=0	DIP09660
DO 1010 IX=1,NACOLX	DIP09670
DO 1010 IY=1,NAROWY	DIP09680
IC=IC+1	DIP09690
IA=IBGNA+(IX-1)*NROWY+IY	DIP09700
IB=IBGNB+(IX-1)*NROWY+IY	DIP09710
WA(IA)=WT(IC)	DIP09720
WB(IB)=WT(IC)	DIP09730
1010 CONTINUE	DIP09740
RETURN	DIP09750
END	DIP09760
C***SUBROUTINE TO COVARIANCE MATRIX BASED ON NUMERICAL INTEGRATION	DIP09770
C***IN THE FREQUENCY DOMAIN ACCORDING TO SIMPSON'S RULE	DIP09780
SUBROUTINE COVSWC(VA,VB,NCHAN,NFREQ,BWPHZ,COVAB)	DIP09790
COMPLEX *16 VA(NCHAN,NFREQ),VB(NCHAN,NFREQ)	DIP09800
COMPLEX *16 COVAB(NCHAN,NCHAN),CSUM,DCABF	DIP09810
REAL *8 SWC(101)	DIP09820
DELTA=BWPHZ/(NFREQ-1)	DIP09830
CALL SIMWC(NFREQ,SWC)	DIP09840

DO 10 ICH=1,NCHAN	DIP09850
DO 10 JCH=1,NCHAN	DIP09860
CSUM=(0.CD0,0.0D0)	DIP09870
DO 20 IFR=1,NFREQ	DIP09880
DCABF=VA(ICH,IFR)*DCONJG(VB(JCH,IFR))	DIP09890
CSUM=CSUM+DCABF*SWC(IFR)	DIP09900
CC WRITE(6,6767)IFR,CSUM	DIP09910
6767 FORMAT(1X,'IFR,CSUM=',I4,2X,2E12.5)	DIP09920
20 CONTINUE	DIP09930
COVAB(ICH,JCH)=DELTA/2.*CSUM	DIF09940
C***NEW LINE TO NORMALIZE COVAB	DIP09950
COVAB(ICH,JCH)=COVAB(ICH,JCH)/BWFHZ	DIP09960
CC WRITE(6,4567)ICH,JCH,COVAB(ICH,JCH)	DIP09970
4567 FORMAT(1X,'ICH,JCH,COVAB(ICH,JCH)=' ,2I4,2X,2E12.5)	DIP09980
10 CONTINUE	DIP09990
RETURN	DIP10000
END	DIP10010
C***SUBROUTINE TO GENERATE SIMPSON'S 1/3 RULE WEIGHTING COEF.	DIP10020
C***INTEGER F(X)DX=(DELTA/3.)*(F(1)+4*F(2)+2*F(3)+4*F(4)+...+F(ODD))	DIP10030
C*** THE SERIES 1 4 2 4 2 4 .....1 ARE SIMPSON'S COEF.	DIP10040
SUBROUTINE SIMWC(NCOEF,SWC)	DIP10050
REAL *8 SWC(NCOEF)	DIP10060
DO 10 N=1,NCOEF	DIP10070
XNN=FLOAT(N)	DIP10080
NN=N/2	DIP10090
TT=XNN/2.	DIP10100
DIF=TT-FLOAT(NN)	DIP10110
NC=2	DIP10120
IF(DIF.EQ.0.) NC=4	DIP10130
IF(N.EQ.1.OR.N.EQ.NCOEF) NC=1	DIP10140
SWC(N)=NC	DIP10150
10 CONTINUE	DIP10160
RETURN	DIP10170
END	DIP10180
C***SUBROUTINE TO COMPUTE RECEIVED VOLTAGES DUE TO JAMMER SOURCES	DIP10190
SUBROUTINE VJAMMR(NJM,NEL,PWRJDB,ICC1,ICC,PS,CZ,Z,CWTA	DIP10200
1,NB,IDMB,NAUX,IAUX,ZLOAD,XJAMIN,YJAMIN,ZJAMIN,	DIP10210
2IFR,NFR,CTPR,STPR,CTDP,VMAINA,VAUXA)	DIP10220
COMPLEX *16 CWTA(NEL,1)	DIP10230
COMPLEX PS(1),CZ(1),Z(ICC1,ICC)	DIP10240
COMPLEX VJM(180),VREFJM	DIP10250
COMPLEX CJ,CSUMA	DIP10260
COMPLEX *16 VMAINA(NJM,NFR)	DIP10270
COMPLEX *16 VAUXA(NAUX,NJM,NFR)	DIP10280
DIMENSION PWRJDB(1),PWRJ(10)	DIP10290
DIMENSION XJAMIN(1),YJAMIN(1),ZJAMIN(1)	DIP10300
INTEGER IAUXA(1)	DIP10310
COMMON/PCFNTR/PCDXIN	DIP10320
COMMON /B/ NGEN,IGEN,THETAS,PHIS,IMUT,IBLTS,IPATRN	DIP10330
COMMON /D/ FGHZ,RLAMDA,IWL,IS,NSCANS	DIP10340
COMMON /WRITE/ IWR	DIP10350
COMMON /CIRCLE/ ICIRC,RADIUS,HLS	
PI=3.141592654	DIP10360
DCR=PI/180.	DIP10370
CJ=(0.,1.)	DIP10380
CINMTR=0.0254	
ISYM=0	DIP10390
C***CONVERT DB TO POWER (RELATIVE TO NOISE)	DIP10400
DO 10 II=1,NJM	DIP10410

	PWRJ(II)=10.*(PWRJDB(II)/10.)	DIP10420
	WRITE(6,66)II,PWRJ(II)	DIP10430
	WRITE(8,66)II,PWRJ(II)	
66	FORMAT(1X,'II,PWRJ IN POWER=',I4,2X,E12.5)	DIP10440
10	CONTINUE	DIP10450
	IF(IFR.GT.1) GO TO 55	DIP10460
	WRITE(6,20)IWL	DIP10470
	DO 5544 IJAM=1,NJM	DIP10480
	WRITE(6,40)	DIP10490
	WRITE(6,50)XJAMIN(IJAM),YJAMIN(IJAM),ZJAMIN(IJAM)	DIP10500
5544	CONTINUE	DIP10510
20	FORMAT(1X,'IWL=',I4)	DIP10520
	WRITE(6,30)	DIP10530
30	FORMAT(1X,'CHANGE NEAR FIELD JAMMER POSITIONS (INCHES)?, ICH=1')	
	READ(6,*)ICH	DIP10550
	IF(ICH.EQ.0) GO TO 55	DIP10560
	DO 8887 IJAM=1,NJM	DIP10570
	WRITE(6,40)	DIP10580
40	FORMAT(1X,'XJAMIN,YJAMIN,ZJAMIN =')	DIP10590
	READ(6,*,END=55)XJAMIN(IJAM),YJAMIN(IJAM),ZJAMIN(IJAM)	DIP10600
	WRITE(6,50)XJAMIN(IJAM),YJAMIN(IJAM),ZJAMIN(IJAM)	DIP10610
50	FORMAT(1X,5F10.3,2X,2I5)	DIP10620
8887	CONTINUE	DIP10630
55	CONTINUE	DIP10640
	PCDX=PCDXIN*CINMTR	
	WRITE(6,4757)IFR	DIP10660
4757	FORMAT(1X,'FREQ. INDEX, IFR=',I4)	DIP10670
60	CONTINUE	DIP10680
	C***ALL DIMENSIONS IN METERS	
	DO 180 IPHACN=1,1	DIP10700
	WRITE(6,2223)IPHACN	DIP10710
2223	FORMAT(1X,'IPHACN=',I4)	DIP10720
	XREFDP=-PCDX/2.+(IPHACN-1)*PCDX	DIP10730
	C***PERFORM JAMMER SOURCE SCAN	DIP10740
	DO 180 IJAM=1,NJM	DIP10750
	X=XJAMIN(IJAM)*CINMTR+PCDX*(IPHACN-1)	
	Y=YJAMIN(IJAM)*CINMTR	
	ZPOS=ZJAMIN(IJAM)*CINMTR	
	WRITE(6,6688)X,Y,ZPOS,XREFDP	DIP10790
6688	FORMAT(1X,'X,Y,ZPOS,XREFDP (METERS)=' ,4F12.4)	
	IF(ICIRC.EQ.0)	
	2CALL NFDPC2(CTPR,STPR,CTDP,STDP,X,Y,ZPOS,XREFDP,1,VJM,VREFJM)	
	IF(ICIRC.EQ.1)	
	2CALL NFDPC2(X,Y,ZPOS,XREFDP,1,VJM,VREFJM)	
	C***NORMALIZE INCIDENT JAMMER POWER	DIP10820
	DO 70 INORM=1,NEL	DIP10830
	VJM(INORM)=VJM(INORM)/VREFJM*SQRT(PWRJ(IJAM))	DIP10840
	WRITE(6,77)INORM,VJM(INORM)	DIP10850
77	FORMAT(1X,'INORM,VJM(INORM) VOLTAGE=' ,I4,2X,2E12.5)	DIP10860
70	CONTINUE	DIP10870
	IF(IMUT.EQ.0) GO TO 90	DIP10880
	C***SOLVE EACH SYSTEM OF EQUATIONS FOR THE UNKNOWN CURRENTS	DIP10890
	IF(IBLTSL.EQ.1) GO TO 80	DIP10900
	I12=1	DIP10910
	IF(IJAM.GT.1.OR.IPHACN.GT.1) I12=2	DIP10920
	WRITE(6,6110)	DIP10930
6110	FORMAT(1X,'CALL CROUT IN VJAMMER')	DIP10940
	CALL CROUT(Z,VJM,ICC1,ICC,ISYM,IWR,I12,NEL)	DIP10950
	GO TO 90	DIP10960

80	IENTRY=4	DIP10970
	IF(IJAM.GT.1.OR.IPHACN.GT.1) IENTRY=3	DIP10980
	CALL BLTSOL(CZ,VJM,PS,NB,IDMB,IENTRY)	DIP10990
	IF(NEL.LT.40) CALL CNORM(VJM,NEL)	DIP11000
90	CONTINUE	DIP11010
	C***COMPUTE RECEIVED VOLTAGES FOR PRESENT SOURCE POSITION	DIP11020
	DO 100 IEL=1,NEL	DIP11030
	VJM(IEL)=VJM(IEL)*ZLOAD	DIP11040
CC	WRITE(6,4456)IEL,VJM(IEL)	DIP11050
4456	FORMAT(1X,'IEL,VJM(IEL) RECEIVED VOLT.=' ,I4,2X,2E12.5)	DIP11060
100	CONTINUE	DIP11070
	C***PERFORM BEAM FORMATION FOR MAIN A	DIP11080
	C***PHASE CENTER A	DIP11090
	CSUMA=(0.0D0,0.0D0)	DIP11100
	DO 110 KC=1,NEL	DIP11110
	CSUMA=CSUMA+VJM(KC)*CWTA(KC,1)	DIP11120
110	CONTINUE	DIP11130
	VMAINA(IJAM,IFR)=CSUMA	DIP11140
	WRITE(6,2222)IJAM,IFR,VMAINA(IJAM,IFR)	DIP11150
2222	FORMAT(1X,'IJAM,IFR,VMAINA= (AFTER B.F.)' ,2I4,2X,2E12.5)	DIP11160
	C***COMPUTE AUXILIARY CHANNEL VOLTAGES	DIP11170
	DO 7000 IAX=1,NAUX	DIP11180
	VAUXA(IAUX,IJAM,IFR)=VJM(IAUXA(IAUX))	DIP11190
7000	CONTINUE	DIP11200
180	CONTINUE	DIP11210
	DO 9000 IJAM=1,NJAMS	DIP11220
CCC	WRITE(6,4433)IJAM,IFR,VMAINA(IJAM,IFR)	DIP11230
4433	FORMAT(1X,'VJAMMR:IJAM,IFR,VMAINA=' ,2I4,2X,2E12.5)	DIP11240
	DO 9001 IAX=1,NAUX	DIP11250
	WRITE(6,3333)IAUX,IJAM,IFR,VAUXA(IAUX,IJAM,IFR)	DIP11260
3333	FORMAT(1X,'VJAMMR:IAUX,IJAM,IFR,VAUXA=' ,3I4,2X,2E12.5)	DIP11270
9001	CONTINUE	DIP11280
9000	CONTINUE	DIP11290
	RETURN	DIP11300
	END	DIP11310
	C***SUBROUTINE TO COMPUTE INTERFERENCE TO NOISE RATIO	DIP11320
	SUBROUTINE INRTIO(WT,COV,NEL,WTCTR,CMPROD,DBINR)	DIP11330
	IMPLICIT REAL *8 (A-H,O-Z)	DIP11340
	COMPLEX *16 WT(NEL,1),COV(NEL,NEL),WTCTR(1,NEL)	DIP11350
	COMPLEX *16 CMPROD(1,NEL),CPROD1(1,1),CPROD2(1,1),CINR	DIP11360
	COMMON /NORMAL/ INRNOR	
	WRITE(12,2222)	DIP11370
2222	FORMAT(1X,'INSIDE INRTIO SUBROUTINE')	DIP11380
	DO 110 I=1,NEL	DIP11390
CC	WRITE(12,445)I,WT(I,1)	DIP11400
445	FORMAT(1X,'I,WT(I,1)=' ,2X,I4,2X,2E12.5)	DIP11410
110	CONTINUE	DIP11420
	CALL CONJTR(WT,NEL,1,WTCTR)	DIP11430
	DO 111 I=1,NEL	DIP11440
CC	WRITE(12,666)I,WT(I,1),WTCTR(1,I)	DIP11450
666	FORMAT(1X,'I,WT,WTCTR=' ,2X,I4,2X,4E12.5)	DIP11460
111	CONTINUE	DIP11470
	CALL CMMULT(WTCTR,COV,1,NEL,NEL,CMPROD)	DIP11480
	CALL CMMULT(CMPROD,WT,1,NEL,1,CPROD1)	DIP11490
	CALL CMMULT(WTCTR,WT,1,NEL,1,CPROD2)	DIP11500
	WRITE(6,333)CPROD1(1,1),CPROD2(1,1)	
	WRITE(8,333)CPROD1(1,1),CPROD2(1,1)	
333	FORMAT(1X,'CPROD1,CPROD2=' ,4E12.5)	DIP11520
	C***INR NORMALIZED	DIP11530

CC	INRNOR=0	DIP11550
	WRITE(6,7739)INRNOR	DIP11560
	WRITE(8,7739)INRNOR	DIP11570
7739	FORMAT(1X,'INR NORMALIZATION PARAMETER, INRNOR=',I4)	DIP11580
	IF(INRNOR.EQ.1) CINR=CPROD1(1,1)/CPROD2(1,1)	
C***	INR NOT NORMALIZED FOR INRNOR=0	
	IF(INRNOR.EQ.0) CINR=CPROD1(1,1)	DIP11600
	DBINR=10.*DLOG10(CDABS(CINR))	DIP11610
	RETURN	DIP11620
	END	DIP11630
	SUBROUTINE CMMULT(A,B,L,M,N,C)	DIP11640
	COMPLEX *16 A(L,M),B(M,N),C(L,N)	DIP11650
	DO 20 I=1,L	DIP11660
	DO 20 J=1,N	DIP11670
	C(I,J)=DCMPLX(0.0D0,0.0D0)	DIP11680
	DO 20 K=1,M	DIP11690
	C(I,J)=C(I,J)+(A(I,K)*B(K,J))	DIP11700
20	CONTINUE	DIP11710
	RETURN	DIP11720
	END	DIP11730
C***	SUBROUTINE TO COMPUTE CONJUGATE TRANSPOSE OF A MATRIX	DIP11740
	SUBROUTINE CONJTR(A,L,M,ACTR)	DIP11750
	COMPLEX *16 A(L,M),ACTR(M,L)	DIP11760
	DO 10 I=1,M	DIP11770
	DO 10 J=1,L	DIP11780
	ACTR(I,J)=DCONJG(A(J,I))	DIP11790
CC	WRITE(12,7766)I,J,A(J,I),ACTR(I,J)	DIP11800
7766	FORMAT(1X,'I,J,A(J I),ACTR(I,J)=' ,2X,2I4,2X,4E12.5)	DIP11810
10	CONTINUE	DIP11820
	RETURN	DIP11830
	END	DIP11840
	SUBROUTINE DCMINV(A,L,M,IDM,NEQ)	DIP11850
	COMPLEX *16 A(IDM,IDM),BIGA,HOLD,DET	DIP11860
	INTEGER L(IDM),M(IDM)	DIP11870
	N=NEQ	DIP11880
	DET=DCMPLX(1.0D0,0.0D0)	DIP11890
	DO 80 K=1,N	DIP11900
	L(K)=K	DIP11910
	M(K)=K	DIP11920
	BIGA=A(K,K)	DIP11930
	DO 20 J=K,N	DIP11940
	DO 20 I=K,N	DIP11950
10	IF(CDABS(BIGA)-CDABS(A(I,J)))15,19,19	DIP11960
15	BIGA=A(I,J)	DIP11970
	L(K)=I	DIP11980
	M(K)=J	DIP11990
19	CONTINUE	DIP12000
20	CONTINUE	DIP12010
	J=L(K)	DIP12020
	IF(J-K)35,35,25	DIP12030
25	CONTINUE	DIP12040
	DO 30 I=1,N	DIP12050
	HOLD=-A(K,I)	DIP12060
	A(K,I)=A(J,I)	DIP12070
30	A(J,I)=HOLD	DIP12080
35	I=M(K)	DIP12090
	IF(I-K)45,45,38	DIP12100
38	CONTINUE	DIP12110
	DO 10 J=1,N	DIP12120

HOLD=-A(J,K)	DIP12130
A(J,K)=A(J,I)	DIP12140
40 A(J,I)=HOLD	DIP12150
45 CONTINUE	DIP12160
DO 55 I=1,N	DIP12170
IF(I-K)50,55,50	DIP12180
50 A(I,K)=A(I,K)/(-BIGA)	DIP12190
55 CONTINUE	DIP12200
DO 65 I=1,N	DIP12210
DO 65 J=1,N	DIP12220
IF(I-K)60,64,60	DIP12230
60 IF(J-K)62,64,62	DIP12240
62 A(I,J)=A(I,K)*A(K,J)+A(I,J)	DIP12250
64 CONTINUE	DIP12260
65 CONTINUE	DIP12270
DO 75 J=1,N	DIP12280
IF(J-K)70,75,70	DIP12290
70 A(K,J)=A(K,J)/BIGA	DIP12300
75 CONTINUE	DIP12310
DET=DET*BIGA	DIP12320
A(K,K)=1.000/BIGA	DIP12330
80 CONTINUE	DIP12340
K=N	DIP12350
100 K=K-1	DIP12360
IF(K)150,150,105	DIP12370
105 I=L(K)	DIP12380
IF(I-K)120,120,108	DIP12390
108 CONTINUE	DIP12400
DO 110 J=1,N	DIP12410
HOLD=A(J,K)	DIP12420
A(J,K)=-A(J,I)	DIP12430
110 A(J,I)=HOLD	DIP12440
120 J=M(K)	DIP12450
IF(J-K)100,100,125	DIP12460
125 CONTINUE	DIP12470
DO 130 I=1,N	DIP12480
HOLD=A(K,I)	DIP12490
A(K,I)=-A(J,I)	DIP12500
130 A(J,I)=HOLD	DIP12510
GO TO 100	DIP12520
150 RETURN	DIP12530
END	DIP12540
C***SUBROUTINE CNORM	DIP12550
C***COMPUTES A NORMALIZED COMPLEX COLUMN VECTOR SUCH THAT THE	DIP12560
C***MAXIMUM ELEMENT HAS UNITY MAGNITUDE.	DIP12570
C	DIP12580
C***PRINTS MAGNITUDE AND PHASE OF NORMALIZED VECTOR	DIP12590
C	DIP12600
SUBROUTINE CNORM(V,N)	DIP12610
C***    V IS THE INPUT COMPLEX COLUMN VECTOR	DIP12620
C***    N IS THE LENGTH OF V	DIP12630
COMPLEX V(1),SS	DIP12640
CNOR=0.0	DIP12650
DO 10 K=1,N	DIP12660
SA=CABS(V(K))	DIP12670
IF(SA.GT CNOR) CNOR=SA	DIP12680
10 CONTINUE	DIP12690
IF(CNOR.LE.0.) CNOR=1.0	DIP12700
DO 30 K=1,N	DIP12710

SS=V(K)	DIP12720
SA=CABS(SS)	DIP12730
SNOR=SA/CNOR	DIP12740
PHR=0.	DIP12750
IF(SA.GT.0.) PHR=ATAN2(AIMAG(SS),REAL(SS))	DIP12760
PH=57.29578*PHR	DIP12770
WRITE(8,20) K,SNOR,SA,PH	DIP12780
20 FORMAT(1X,I5,F10.6,3X,E15.3,F10.0)	DIP12790
30 CONTINUE	DIP12800
RETURN	DIP12810
END	DIP12820
SUBROUTINE GETCP2(RCPU)	
REAL ETIME,TARRAY(2),RCPU	
TIME=ETIME(TARRAY)	
RCPU=TARRAY(1)	
RETURN	
END	
C***SUBROUTINE TO COMPUTE INDUCED VOLTAGE BETWEEN PROBE AND	YDI00010
C***DIPOLE ARRAY ELEMENTS	
C***RING ARRAY	
SUBROUTINE NFDPC2(XP,YP,ZP,XREF,V,VREF)	
C***DISTANCES ARE IN METERS	
COMPLEX V(1),VD,VR1,VREF	
COMPLEX *16 DZABG	YDI00060
COMMON/A/DX,DY,NCOLX,NROWY,NEL,HZ,HL,ARAD,ZLOAD,ZCHAR	YDI00070
COMMON /CIRCLE/ ICIRC,RADIUS,HLS	
C***NOTE: AA,BB,... FOR PROBE 11,22,... FOR DIPOLE	YDI00120
PI=3.1415926535	
DCR=PI/180.	
C***PROBE DIMENSIONS	
XAA=XP	YDI00260
YBB=YP	YDI00270
ICC=XP	YDI00280
YAA=YF-HLS	
YBB=YP	YDI00300
YCC=YP+HLS	
785 ZAA=ZP	
ZBB=ZP	YDI00330
ZCC=ZP	
IC=0	YDI00430
C****CIRCULAR DIPOLE ARRAY ELEMENTS	
DELPHI=360./NEL	
DO 10 IX=1,NEL	
PHI=DELPHI*(IX-1)	
XD=RADIUS*COS(PHI*DCR)	
ZD=RADIUS*SIN(PHI*DCR)	
DIST=SQRT((XP-XD)**2+(YP-ZD)**2)	
IF(DIST.LT.ARAD) XD=XD+ARAD	
X11=XD	
X22=XD	YDI00490
X33=XD	
Y11=YP-HL	
Y22=YP	
Y33=YP+HL	
Z11=ZD	
Z22=ZD	
Z33=ZD	
9446 IC=IC+1	YDI00650
CC WRITE(6,2233)IX,IY,XD,YD	YDI00660

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2233 FORMAT(1X,'IX,IY,IX,YD=',2X,2I4,2X,2F12.5) YDI00670
CC WRITE(6,7854)XAA,XBB,XCC,YAA,YBB,YCC,ZAA,ZBB,ZCC
7854 FORMAT(1X,'XYZABC=',9E12.5)
CC WRITE(6,7855)X11,X22,X33,Y11,Y22,Y33,Z11,Z22,Z33
7855 FORMAT(1X,'XYZ123=',9E12.5)
CALL DSZABG(XAA,XBB,XCC,YAA,YBB,YCC,ZAA,ZBB,ZCC,X11,X22,X33, YDI00680
2Y11,Y22,Y33,Z11,Z22,Z33,DZABG) YDI00690
VD=DZABG YDI00700
CC WRITE(6,33)IC,VD
33 FORMAT(1X,'IC,VD=',2X,I5,2E12.5)
V(IC)=VD
VAMPDB=20.*ALOG10(CABS(V(IC))) YDI00780
VPHASE=ATAN2(AIMAG(V(IC)),REAL(V(IC)))*180./3.141592654 YDI00790
CC WRITE(6,4455)IC,VAMPDB,VPHASE YDI00800
4455 FORMAT(1X,'IC,VAMPDB,VPHASE=',2X,I4,2X,2F12.2) YDI00810
10 CONTINUE YDI00820
C***COMPUTE REFERENCE VOLTAGE (FICTITIOUS ELEMENT AT XREF, Y=0) YDI00830
C***SET XREF=RADIUS, THIS MAKES ELEMENT 1 THE REFERENCE
XREF=RADIUS
C***SET XREF=ARAD, (REF. CLOSE TO THE ORIGIN)
XREF=ARAD
X11=XREF
X22=XREF YDI00870
X33=XREF
Y11=-HL
Y22=0.0 YDI00980
Y33=HL
Z11=0.0
Z22=0.0
Z33=0.0
9267 CALL DSZABG(XAA,XBB,XCC,YAA,YBB,YCC,ZAA,ZBB,ZCC,X11,X22,X33, YDI01000
2Y11,Y22,Y33,Z11,Z22,Z33,DZABG) YDI01010
VR1=DZABG YDI01020
VREF=VR1
99 RETURN YDI01080
ENL YDI01090
C***SUBROUTINE TO COMPUTE MUT. IMPED. BETWEEN STRAIGHT DIPOLES
C***ARRANGED IN A RING ARRAY (CIRCLE)
SUBROUTINE CADZA2(CTDP,STDP,IGRNDP,ICC1,ICC,Z)
COMPLEX ZMA,ZABG,Z(ICC1,ICC)
COMMON /A/ DX,DY,NCOLX,NROWY,NEL,HZ,HL,ARAD,ZLOAD,ZCHAR
COMMON /CIRCLE/ ICIRC,RADIUS,HLS
C***ALL DIMENSIONS IN METERS
PI=3.1415926535
DCR=PI/180.
C***FIXED POSITION FOR ELEMENT 1
XAA=RADIUS
XBB=RADIUS
XCC=RADIUS
YAA=-HL
YBB=0.0
YCC=HL
ZAA=0.0
ZBB=0.0
ZCC=0.0
Y11=YAA
Y22=YBB
Y33=YCC

```



```

C***VARIABLE POSITION FOR RING ARRAY ELEMENTS
  DELPHI=360./NEL
  IC=0
  DO 20 I=1,NEL
  IC=IC+1
  PHI=DELPHI*(I-1)*DCR
  XD=RADIUS*COS(PHI)
  ZD=RADIUS*SIN(PHI)
  X11=XD
  X22=XD
  X33=XD
  IF(I.EQ.1) X11=X11+ARAD
  IF(I.EQ.1) X22=X22+ARAD
  IF(I.EQ.1) X33=X33+ARAD
  Z11=ZD
  Z22=ZD
  Z33=ZD
CC  WRITE(6,87)IC
87  FORMAT(1X,'IC=',I5)
CC  WRITE(6,88)XAA,XBB,XCC,YAA,YBB,YCC,ZAA,ZBB,ZCC
88  FORMAT(1X,'XYZABC=',9E12.4)
CC  WRITE(6,89)X11,X22,X33,Y11,Y22,Y33,Z11,Z22,Z33
89  FORMAT(1X,'XYZ123=',9E12.4)
  ZMA=ZABG(XA,XBB,XCC,YAA,YBB,YCC,ZAA,ZBB,ZCC,X11,X22,X33,
  Y11,Y22,Y33,Z11,Z22,Z33)
  Z(1,IC)=ZMA
  IF(IC.EQ.1) Z(1,1)=Z(1,1)+ZLOAD
20  CONTINUE
  DO 40 I=1,NEL
  IF(I.LT.9)WRITE(6,30)I,Z(1,I)
  WRITE(8,30)I,Z(1,I)
30  FORMAT(1X,'Z(1,',I4,')=',2E12.5)
40  CONTINUE
  RETURN
  END

*****file zabgenloss.f*****
C***PROGRAM TO CALCULATE MUTUAL IMPEDANCE BETWEEN TWO DIPOLES      ZAB00010
C***WITH ARBITRARY LENGTH AND ORIENTATION.  A PIECEWISE-          ZAB00020
C***SINUSOIDAL CURRENT DISTRIBUTION IS ASSUMED.                   ZAB00030
  COMPLEX FUNCTION ZABG(X1,X2,X3,Y1,Y2,Y3,Z1,Z2,Z3,XA,XB,XC,YA,YB,YCZAB00040
  2,ZA,ZB,ZC)                                                       ZAB00050
  COMPLEX P11,P12,P21,P22,Q11,Q12,Q21,Q22,R11,R12,R21,R22         ZAB00060
  COMPLEX S11,S12,S21,S22,JCOM,GAM,CGDS,SGDS,SGDT,ETA,EP3        ZAB00070
  COMPLEX EGDS,EGDT
  COMMON /F/ FHZ,ER3,SIG3,TD3
C***ALL DIMENSIONS IN METERS
  PI=3.141592654
  TPI=2.*PI
  B=TPI
  JCOM=(0.,1.)                                                     ZAB00090
  EO=8.854E-12
  UO=1.2566E-3
  OMEGA=TPI*FHZ
  IF(SIG3.LT.0.)EP3=ER3*EO*CMPLX(1.,-TD3)                         WIR01670
  IF(TD3.LT.0.)EP3=CMPLX(ER3*EO,-SIG3/OMEGA)                     WIR01720
  ETA=CSQRT(UO/EP3)                                                WIR01730
  GAM=OMEGA*CSQRT(-UO*EP3)                                         WIR01740
  WIR01750

```

```

AM=0.0001
IF(CABS(GAM*AM).GT.0.06) WRITE(6,7923)AM
7923 FORMAT(1X,'CABS(GAM*AM) IS GREATER THAN 0.06, AM=',E14.5)
INT=0
XBA=XB-IA
YBA=YB-YA
ZBA=ZB-ZA
X21=X2-X1
Y21=Y2-Y1
Z21=Z2-Z1
DS=SQRT(XBA*XBA+YBA*YBA+ZBA*ZBA)
DT=SQRT(X21*X21+Y21*Y21+Z21*Z21)
CC DSK=B*DS
CC DTK=B*DT
CC CGDS=CMPLX(COS(DSK),0.0)
CC SGDS=CMPLX(0.0,SIN(DSK))
CC SGDT=CMF(0.0,SIN(DTK))
C***FOR LOSSY MEDIUM THE NEXT LINES ARE APPROPRIATE
EGDS=CEXP(GAM*DS)
EGDT=CEXP(GAM*DT)
CGDS=(EGDS+1./EGDS)/2.
SGDS=(EGDS-1./EGDT)/2.
SGDT=(EGDT-1./EGDT)/2.
CC WRITE(6,1345)XA,XB,YA,YB,ZA,ZB
1345 FORMAT(1X,'XYZAB=',6E14.5)
CC WRITE(6,1346)X1,X2,Y1,Y2,Z1,Z2
1346 FORMAT(1X,'XYZ12=',6E14.5)
CALL GGS(XA,YA,ZA,XB,YB,ZB,X1,Y1,Z1,X2,Y2,Z2,AM,
2DS,CGDS,SGDS,DT,SGDT,INT,ETA,GAM,P11,P12,P21,P22)
CALL GGS(XA,YA,ZA,XB,YB,ZB,X2,Y2,Z2,X3,Y3,Z3,AM,
2DS,CGDS,SGDS,DT,SGDT,INT,ETA,GAM,Q11,Q12,Q21,Q22)
CALL GGS(XB,YB,ZB,XC,YC,ZC,X1,Y1,Z1,X2,Y2,Z2,AM,
2DS,CGDS,SGDS,DT,SGDT,INT,ETA,GAM,R11,R12,R21,R22)
CALL GGS(XB,YB,ZB,XC,YC,ZC,X2,Y2,Z2,X3,Y3,Z3,AM,
2DS,CGDS,SGDS,DT,SGDT,INT,ETA,GAM,S11,S12,S21,S22)
ZABG=P22+Q21+R12+S11
CC WRITE(6,7898)ZABG
7898 FORMAT(1X,'EXITING ZABG WITH ZABG=',2E14.5)
RETURN
END
*****file dzabgnloss.f*****
C***DOUBLE PRECISION VERSION
C***PROGRAM TO CALCULATE MUTUAL IMPEDANCE BETWEEN TWO DIPOLES
C***WITH ARBITRARY LENGTH AND ORIENTATION. A PIECEWISE-
C***SINUSOIDAL CURRENT DISTRIBUTION IS ASSUMED.
SUBROUTINE DSZABG(SX1,SX2,SX3,SY1,SY2,SY3,SZ1,SZ2,SZ3,
2SXA,SXB,SXC,SYA,SYB,SYC,SZA,SZB,SZC,DZABG)
IMPLICIT REAL*8 (A-H,O-Z)
COMPLEX*16 P11,P12,P21,P22,Q11,Q12,Q21,Q22,R11,R12,R21,R22
COMPLEX*16 S11,S12,S21,S22,JCOM,GAM,CGDS,SGDS,SGDT,ETA
COMPLEX*16 DZABG,EP3,EGDS,EGDT
REAL*4 SX1,SX2,SX3,SY1,SY2,SY3,SZ1,SZ2,SZ3
REAL*4 SXA,SXB,SXC,SYA,SYB,SYC,SZA,SZB,SZC
REAL*4 FHZ,ER3,SIG3,TD3
COMMON /F/ FHZ,ER3,SIG3,TD3
JCOM=(0.D0,1.D0)
PI=3.1415926535898D0
TPI=2.0D0*PI

```

ZAB00130  
ZAB00140  
ZAB00150  
ZAB00160  
ZAB00170  
ZAB00180  
ZAB00190  
ZAB00200  
ZAB00210  
ZAB00220  
ZAB00230  
ZAB00240  
ZAB00250  
ZAB00260

ZAB00270  
ZAB00280  
ZAB00290  
ZAB00300  
ZAB00310  
ZAB00320  
ZAB00330  
ZAB00340  
ZAB00350

ZAB00360  
ZAB00370

DZA00020  
DZA00030  
DZA00040  
DZA00050  
DZA00060  
DZA00070  
DZA00080  
DZA00090  
  
DZA00110  
DZA00120  
  
DZA00140

B=TPI	
EO=8.854D-12	
UO=1.2566D-6	
OMEGA=TPI*FHZ	WIRO1670
CC WRITE(6,2843)OMEGA	WIRO1680
2843 FORMAT(1X,'OMEGA=',E12.5)	WIRO1690
IF(SIG3.LT.0.0D0)EP3=ER3*EO*DCMPLX(1.0D0,-TD3)	WIRO1720
IF(TD3.LT.0.0D0)EP3=DCMPLX(ER3*EO,-SIG3/OMEGA)	WIRO1730
CC WRITE(6,7755)ER3,EO,EP3	
7755 FORMAT(1X,'ER3,EO,EP3=',4E12.5)	
ETA=CDSQRT(UO/EP3)	WIRO1740
GAM=OMEGA*CDSQRT(-UO*EP3)	WIRO1750
C**COMPUTE GAMMA BY EQUATION IN HYAT PAGE 333	
CC GAM=JCOM*OMEGA*CDSQRT(UO*EP3)*CDSQRT(1.D0-JCOM*SIG3/(OMEGA*EP3))	
CC WRITE(6,8888)GAM	
8888 FORMAT(1X,'HYAT GAM=',2E12.5)	
AM=0.0001D0	
INT=0	DZA00180
X1= SX1	DZA00190
X2= SX2	DZA00200
X3= SX3	DZA00210
Y1= SY1	DZA00220
Y2= SY2	DZA00230
Y3= SY3	DZA00240
Z1= SZ1	DZA00250
Z2= SZ2	DZA00260
Z3= SZ3	DZA00270
XA= SXA	DZA00280
XB= SXB	DZA00290
XC= SXC	DZA00300
YA= SYA	DZA00310
YB= SYB	DZA00320
YC= SYC	DZA00330
ZA= SZA	DZA00340
ZB= SZB	DZA00350
ZC= SZC	DZA00360
XBA= XB-XA	DZA00370
YBA= YB-YA	DZA00380
ZBA= ZB-ZA	DZA00390
X21= X2-X1	DZA00400
Y21= Y2-Y1	DZA00410
Z21= Z2-Z1	DZA00420
DS=DSQRT(XBA*XBA+YBA*YBA+ZBA*ZBA)	DZA00430
DT=DSQRT(X21*X21+Y21*Y21+Z21*Z21)	DZA00440
CC DSK=B*DS	DZA00450
CC DTK=B*DT	DZA00460
CC CGDS=DCMPLX(DCOS(DSK),0.0D0)	DZA00470
CC SGDS=DCMPLX(0.0D0,DSIN(DSK))	DZA00480
CC SGDT=DCMPLX(0.0D0,DSIN(DTK))	DZA00490
EGDS=CDEXP(GAM*DS)	
EGDT=CDEXP(GAM*DT)	
CGDS=(EGDS+1.0D0/EGDS)/2.0D0	
SGDS=(EGDS-1.0D0/EGDS)/2.0D0	
SGDT=(EGDT-1.0D0/EGDT)/2.0D0	
CALL DGGG(XA,YA,ZA,XB,YB,ZB,X1,Y1,Z1,X2,Y2,Z2,AM,	DZA00500
2DS,CGDS,SGDS,DT,SGDT,INT,ETA,GAM,P11,P12,P21,P22)	DZA00510
CALL DGGG(XA,YA,ZA,XB,YB,ZB,X2,Y2,Z2,X3,Y3,Z3,AM,	DZA00520
2DS,CGDS,SGDS,DT,SGDT,INT,ETA,GAM,Q11,Q12,Q21,Q22)	DZA00530

CALL DGGG(XB,YB,ZB,XC,YC,ZC,X1,Y1,Z1,X2,Y2,Z2,AM,	DZA00540
2DS,CGDS,SGDS,DT,SGDT,INT,ETA,GAM,R11,R12,R21,R22)	DZA00560
CALL DGGG(XB,YB,ZB,XC,YC ZC,X2,Y2,Z2,X3,Y3,Z3,AM,	DZA00560
2DS,CGDS,SGDS,DT,SGDT,INT,ETA,GAM,S11,S12,S21,S22)	DZA00570
DZABG=P22+Q21+R12+S11	DZA00580
CC WRITE(6,8899)DZABG	
8899 FORMAT(1X,'EXITING DZABG, DZABG=',2E14.5)	DZA00590
RETURN	DZA00600
END	

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